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Microgravity Combustion Diagnostics Workshop

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Proceedings of a workshop held at
NASA Lewis Research Center
Cleveland, Ohio
July 28-29, 1987

NASA

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Edited by
Gilbert J. Santoro, Paul S. Greenberg,
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Information Branch

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PROCEEDINGS OF THE MICROGRAVITY COMBUSTION DIAGNOSTICS WORKSHOP

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INTRODUCTION

Through the Microgravity Science and Applications Division (MSAD) of the Office of Space Science and Applications (OSSA) at NASA Headquarters, a program entitled "Advanced Technology Development (ATD)" was initiated with the objective of providing advanced technologies that will enable the development of microgravity science and applications experimental hardware to enhance the scientific integrity and yield of space flight experiments. The technologies to be selected must not be in the critical path of ongoing programs or of near-term facility development programs. Among the light ATD projects one, Microgravity Combustion Diagnostics (MCD), had the objective of developing advanced diagnostic techniques and technologies to provide nonperturbing measurements of combustion characteristics and parameters that will enhance the scientific integrity and quality of microgravity combustion experiments. The Space Experiments Division (SED) of the Lewis Research Center in Cleveland, Ohio, was assigned the task of managing this project. The approach to this effort was typical of all the ATD projects, namely, of defining the requirements, assessing the technology, and studying possible trade-offs. As a part of this approach a small group of laser combustion diagnosticians met with a group of microgravity combustion experimenters to engage in workshop discussions of science requirements, of the state-of-the-art of laser diagnostic technology, and of the direction and planning for near-, intermediate-, and long-term programs. (Nonlaser combustion diagnostics will be more fully addressed separately, although some mention of them was made in this workshop.) This report is the proceedings the Microgravity Combustion Diagnostics Workshop held at NASA Lewis on July 28 and 29, 1987.[1]

Most of the agenda consisted of discussions. To have meaningful discussions in a two-day period, it was necessary to limit the number of participants. Of the two groups of participants mentioned above, the microgravity combustion experimenters were mostly Lewis personnel, as Lewis is the focal point of NASA's microgravity combustion effort. The other group consisted of nine members of the laser combustion diagnostics community representing academia, industry, and government. The total number of people in attendance was 32, which included pertinent personnel outside of the two main groups. Appendix A lists all the participants and their affiliation, as well as workshop committee members.

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[1] Prior to the workshop, the scope of the project was extended to include fluids. The project is now designated as Microgravity Fluids and Combustion Diagnostics (MFCD). The planning for the workshop was too far along to reflect this change in scope. Therefore, this workshop considered combustion diagnostics only, leaving the consideration of fluids diagnostics to a later date.

The agenda consisted of three parts: introduction, background presentations, and technical discussions. The welcoming address was given by William Masica, Chief of the Lewis Space Experiments Division. The diagnosticians were briefed on NASA's microgravity combustion efforts and with the restraints involved in conducting experiments in a low-gravity environment, thus providing the diagnosticians with sufficient background information to supply fully informed recommendations. The discussions items in the agenda were selected to provide some structure to the discussion and to act as a guide for the discussion leaders. Yet it was felt necessary to incorporate enough flexibility to allow for unforeseen subjects and miscalculations in allotted times. The time set aside for Section IV, "Discussion Summary," scheduled for the afternoon of the second day, was considered expendable for this purpose. And, in fact, that time period was used for the presentation of selected low-gravity combustion experiment results in order to solicit comments and recommendations from the diagnosticians.

The success of the workshop was judged on the basis of obtaining the following information:

- A specific plan for ground-based microgravity work to be conducted at Lewis, referred to as the near-term effort.

- The general direction to take in the intermediate-term effort, which covers a period of 5 or more years, with the emphasis on combustion experiments aboard the space station. The workshop organizers also sought direction about the probability of miniaturizing and hardening laser systems for combustion studies in space.

- A recommendation of a mechanism to identify, to evaluate the applicability, and, when applicable, to assimilate into the MCD project new developments occurring in laser combustion diagnostics.

- An evaluation of the idea to modularize laser combustion diagnostic systems for applications aboard the space station.

BACKGROUND PRESENTATIONS

Organizational Background

The organizational background presentations were divided into two parts: (1) an overview presented by Jack Salzman and (2) the multiuser facilities and advanced technology development (ATD) programs, of which MCD is one, presented by Richard Parker. In the former presentation NASA's organization was given with those departments associated with the microgravity programs highlighted (see figs. 1 to 3). Note the matrix nature of the microgravity effort at NASA as it cuts across functional organizational lines. For example, functionally, Lewis is managed under the Office of Aeronautics and Space Technology (OAST), but the SED programs are funded by MSAD of OSSA. Although SED, under the Space Flight Systems Directorate, is the focal group at Lewis for the microgravity programs, the Materials Division, under the Aerospace Technology Directorate, is substantially involved, and the Engineering Directorate provides engineering support. The specific objectives of the space experiments at Lewis are listed below:

- Develop the in-space R&T base for advanced space missions and operations by conducting phased experimental projects using ground-based research facilities, STS, and space station.

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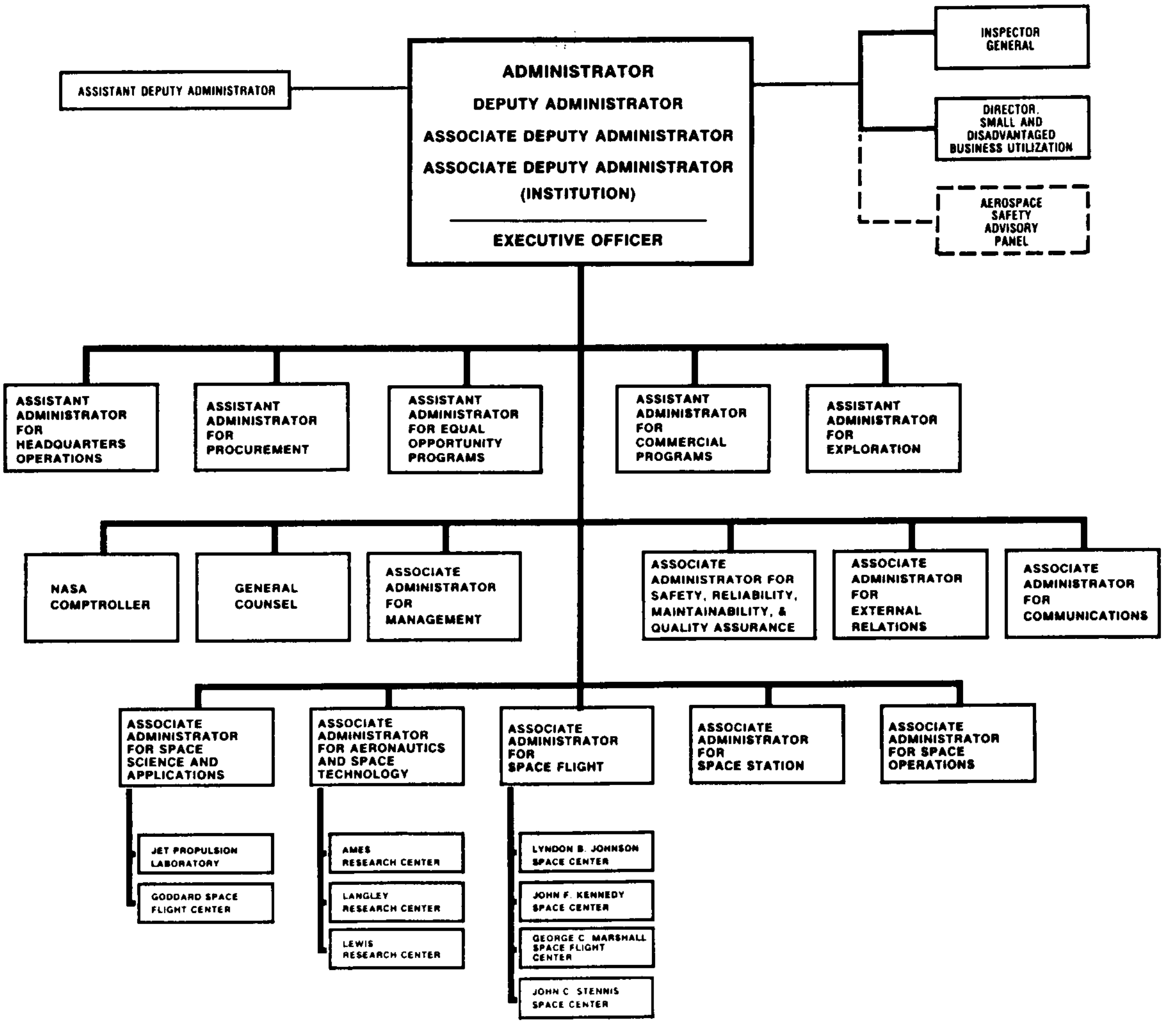

FIGURE 1. - NASA HEADQUARTERS, WASHINGTON, D.C.

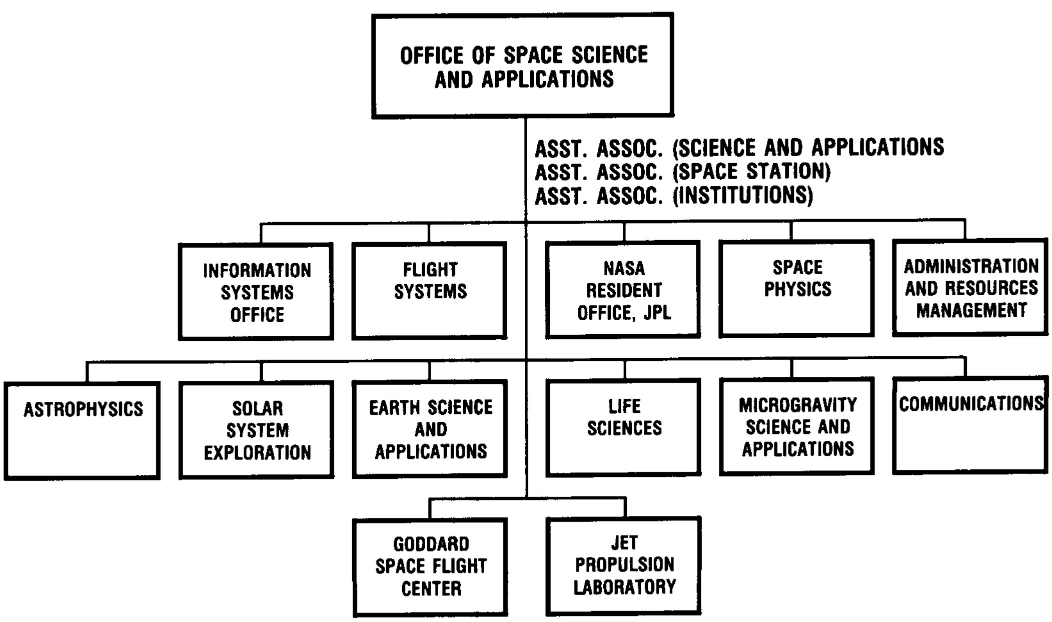

FIGURE 2. - NASA HEADQUARTERS, OFFICE OF SPACE SCIENCE AND APPLICATIONS.

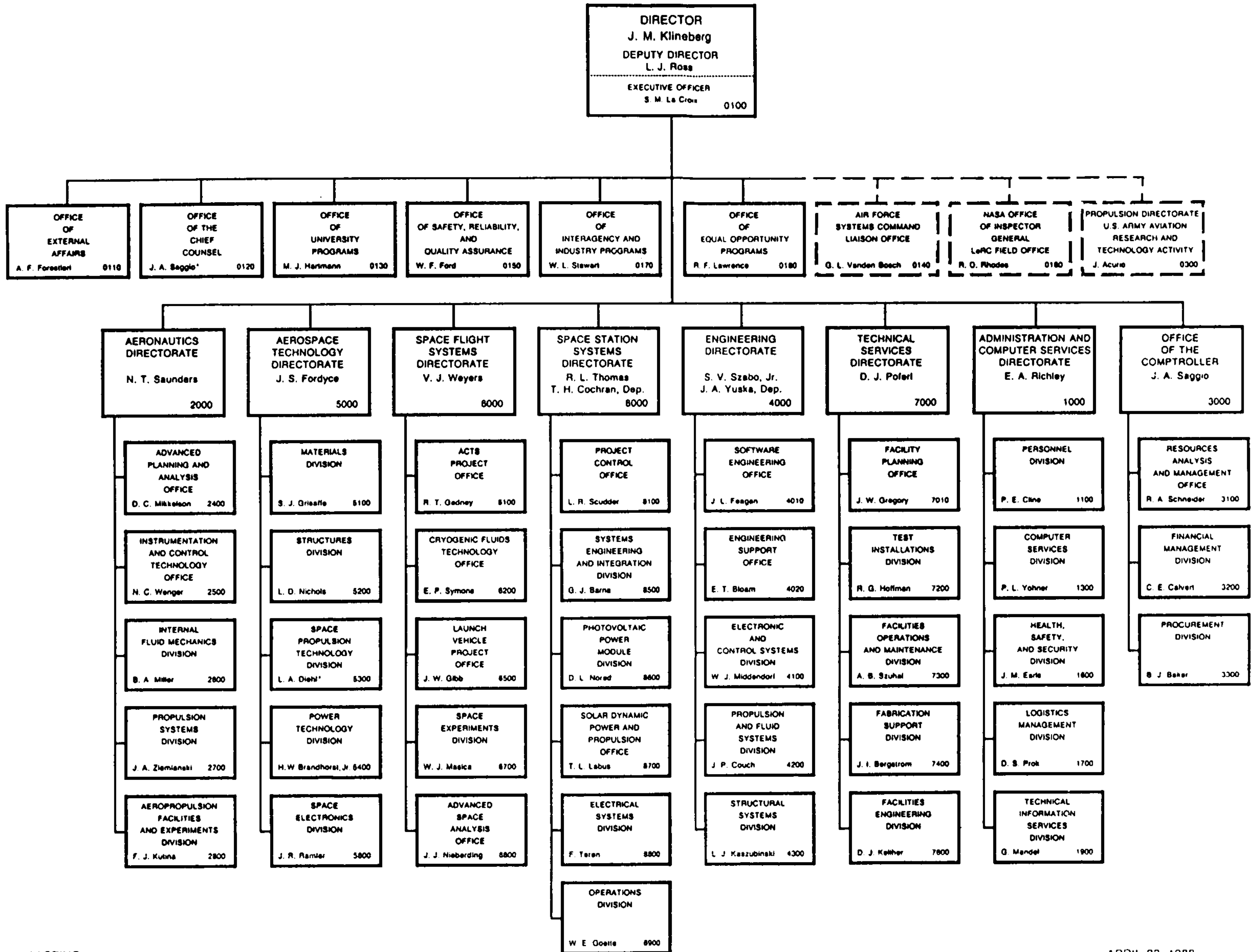

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FIGURE 3. - LEWIS RESEARCH CENTER, CLEVELAND, OHIO.

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- Improve understanding of the role of gravity in the fundamentals of combustion science, materials science and processing, fluid physics, and chemistry.
- Implement lead NASA center role for in-space cryogenic fluid management technology.
- Develop experiment hardware for space station microgravity science and applications and contribute to utilization planning activities.
- Assist in the identification, selection, and implementation of flight experiments with commercial applications.

Lewis managed microgravity ground-based science programs were presented; the presentation covered such areas as electronic materials, combustion science, fluid physics, metals and alloys, ceramic and glasses, and physics and chemistry experiments. The 13 in-house research programs were also listed as well as the 14 flight programs. The latter programs are shown here in table I.

The modular multiuser facilities program is part of an ongoing effort to define and develop the experimental facilities aboard the United States Laboratory (USL) module of the space station (see fig. 4). The facilities to be developed along with the responsible NASA centers are given in table II.

Lewis, via a joint cooperative agreement (JCA) among the centers, is the lead center for the fluid physics/dynamics facility and the microgravity combustion facility. The latter is essentially a host module containing all the support systems for operating interchangeable specific combustion experiments (see fig. 5). The projects of the Advanced Technology Development (ATD) Program are given in table III.

TABLE I. - MICROGRAVITY SCIENCE AND APPLICATIONS AND LEWIS MICROGRAVITY SCIENCE FLIGHT EXPERIMENTS

	P.I.[a]/Affiliation	Carrier[b]	Hardware delivery date
Combustion science			
1. Solid surface combustion	Altenkirch/U. Kentucky	SLS-1, middeck	9/87
2. Particle cloud combustion	Berlad/U.C. San Diego	MSL-6	1/90
3. Droplet burning	Williams/Princeton	Middeck	12/89
4. Gas jet diffusion flames	Edelman/SAI	TBD[c]	TBD
Materials science			
5. Alloy undercooling	Flemings/MIT	EML; MSL (flew on STS 61-C, 1/12/86)	NA
6. Binary alloy solidifcation	Laxmanan/CWRU, LeRC	GPF; MSL-3	NA
7. GaAs crystal growth	Kafalas/GTE	GAS or MSL-3	11/87
8. Isothermal dendritic growth	Glicksman/RPI	MSL-4, -5	5/89
Fluid physics			
9. EMD flow in metals	Szekely/MIT	EML; MSL	NA
10. Surface tension driven convection	Ostrach/CWRU	MAR, Spacelab	11/89
11. Critical fluid light Scattering	Gammon/UM	MSL-7	7/90
12. Pool boiling	Merte/U. Michigan	GAS	TBD
Instrumentation			
13. Space accelerometer system (SAMS)	Chase/LeRC	GAS, MSL-3	4/88
14. SAMS follow-on	Chase/LeRC	Middeck, MSL, spacelab	TBD

[a]PI = Principle Investigator.
[b]Designated location of the experiment on the space shuttle.
[c]TBD = To be determined.

TABLE II. - MODULAR, MULTIUSER FACILITIES TO BE DEFINED AND DEVELOPED UNDER INTERCENTER JOINT COOPERATIVE AGREEMENTS (JCA)

Facility	Lead/support centers[a]
Advanced protein crystal growth facility	MSFC/JPL
Biotechnology facility	JSC/MSFC
Fluid physics/dynamics facility	LeRC/MSFC, JPL
Microgravity combustion facility	LeRC
Modular containerless processing facility	JPL/MSFC, LeRC
Modular multizone furnace facility	MSFC/JPL, LaRC

[a]See appendix B.

TABLE III. - ADVANCED TECHNOLOGY DEVELOPMENT PROGRAM PROJECTS

ADT Project	Lead/support center
Biosensors	JSC
High resolution, high frame rate video technology	LeRC/MSFC, LaRC
High-temperature furnace technology	MSFC/LeRC, JPL
Interface measurements	LaRC
Laser light scattering	LeRC/MSFC
Microgravity fluids and combustion diagnostics[a]	LeRC/MSFC, JPL, LaRC
Noncontact temperature measurements	JPL/LeRC, MSFC, LaRC
Vibration isolation technology	LeRC/MSFC

[a]The scope of the Microgravity Combustion Diagnostic (MCD) project was expanded to include fluids.

The MCD project is now called Microgravity Fluids and Combustion Diagnostics (MFCD). This workshop was held before the expansion of the project's scope. The combustion diagnostics systems, which will be developed from this project, will be coupled, in a manner yet to be defined, with the combustion experiments in the Modular Combustion Facility .

Technical Background

Lewis combustion program requirements. - Kurt Sacksteder presented the microgravity combustion program requirements. He listed the rationale for conducting low-gravity experiments, in that they provide

- Observation of gravitational effects
  - Buoyancy driven convection
  - Sedimentation of multiphase systems
- Observation of nongravitational mechanisms normally obscured by buoyancy convection
  - Surface tension phenomena
  - Low-speed forced flows
  - Surface jets
  - Diffusion

FIGURE 4. - SPACE STATION UNITED STATES LABORATORY (USL) MODULE.

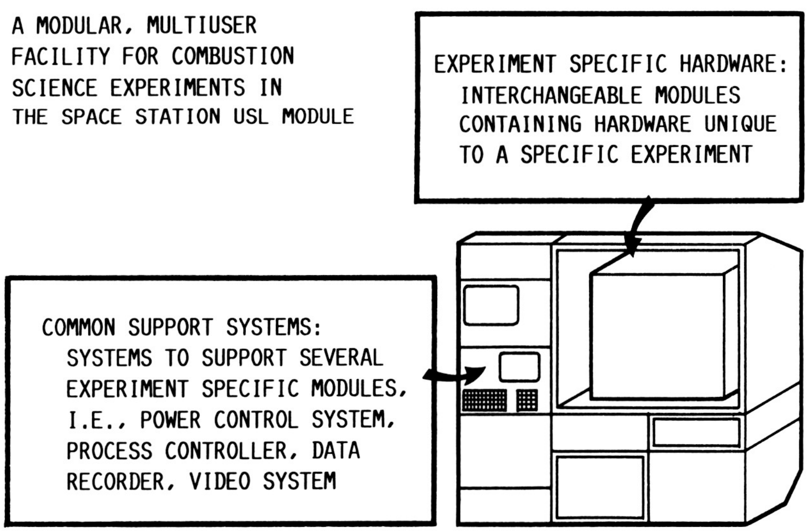

FIGURE 5. - MODULAR COMBUSTION FACILITY BASELINE CONCEPT.

- Unique initial or boundary conditions
  - Isolated masses
  - Uniform particle distributions

He also listed the limitations imposed on diagnostics systems operating in low-gravity environments, particulary in space:

- Mechanical loads
- Size limitations
- Weight limitations
- Power consumption limits
- Hands-on requirements

Nonlaser diagnostics. - To indicate an awareness of the existence of diagnostic methods which are applicable to combustion experiments other than laser techniques, Kermit Smyth presented the results of some of his work at the National Bureau of Standards. He characterized the chemical structure of a laminar CH_4/air diffusion flame using a combination of diagnostic methods; primarily, mass spectrometry and thermocouples; and, secondarily, laser-based optics such as laser induced fluorescence (LIF), multiphoton ionization, Rayleigh scattering, and laser Doppler velocimetry (LDV). The goal of this work is to better understand chemical processes of molecular growth in flaming hydrocarbon combustion processes by which small molecules grow, become larger molecules, and eventually form soot. By using the above diagnostic techniques, profiles of temperature, species concentrations and velocities were generated. The point was made that only after all of this information has been gathered can an analysis of the reaction kinetics be contemplated. A schematic of the mass spectrometer set up is given in figure 6. In this study the spatial resolution of the mass spectrometric measurements were compared with the measurements from the other diagnostics and the information is reproduced in table IV.

Finally, the advantages and disadvantages of mass spectrometric sampling were listed:

Advantages
- Quantitative concentration measurements
- Wide range of species
- Species specificity
- Temperature measurements
- Simultaneous multiple species and temperature

Disadvantages
- Limited real time resolution: 300 msec using a quartz microprobe, 1 msec using molecular beam sampling
- Possible probe perturbation, particularly for low velocity flow fields

Temperature measurements using the mass spectrometer is based on the signal being proportional to the molecular flow rate, which, in turn, is related to the temperature. The temperature measuring procedure was demonstrated using argon. The calculated temperatures are compared with those measured with thermocouples (see fig. 7).

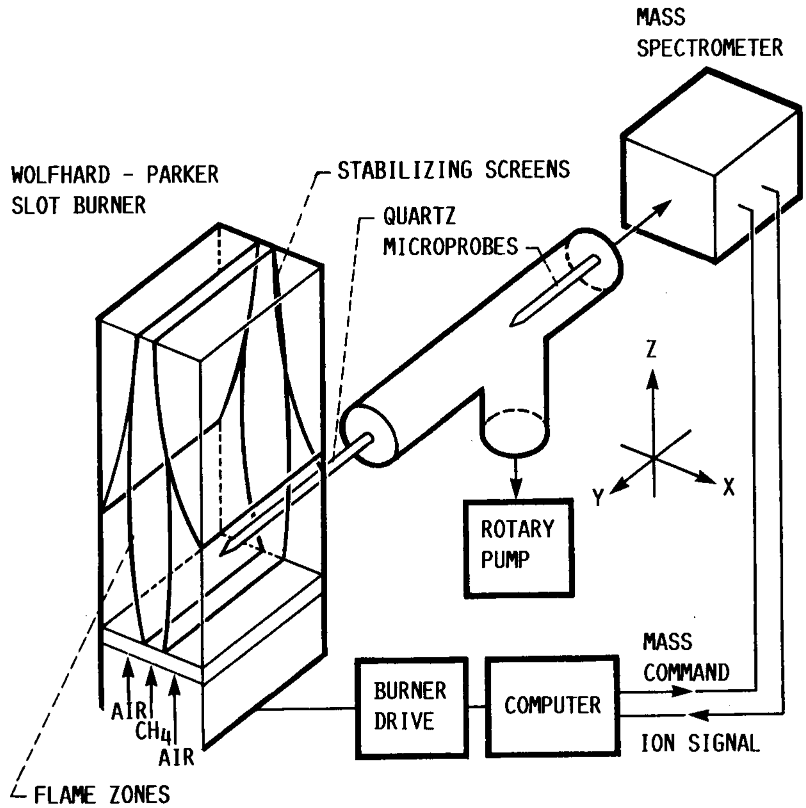

FIGURE 6. - MASS SPECTROMETER.

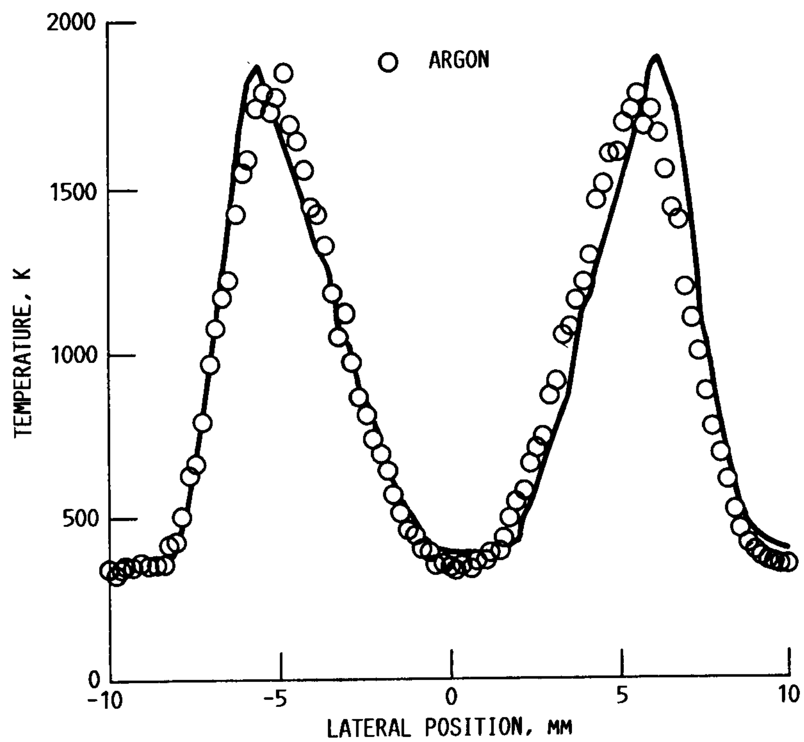

FIGURE 7.- CALCULATED VS MEASURED (THERMOCOUPLES) TEMPERATURES.

TABLE IV. - COMPARISON OF SPATIAL RESOLUTION OF VARIOUS DIAGNOSTIC TOOLS

Measurement	Spatial resolution, mm
Mass spectrometrometry:	
Quartz microprobe orifice diameter	0.14
Effective spatial resolution	.7
Temperature:	
Thermocouple wire	.125
Thermocouple bead	.18
Laser-based optics:	
Laser induced fluorescence	.3
Multiphoton ionization	<.1
Rayleigh scattering	.2
Laser Doppler velocimetry	.2

Microgravity ground-based accommodations. - Jack Lekan presented the microgravity ground-based accommodations of the research facilities and aircraft utilized in conducting ground-based microgravity research:

- Lewis 2.2-Second Drop Tower
- Lewis 5.18-Second Zero-Gravity Facility
- Lewis Learjet Model 25
- JSC KC-135

2.2-Second drop tower: A schematic of the 2.2-Second Drop Tower is shown in figure 8, its specifications and characteristics are given in table V, and its description and mode of operation are given below:

- The experimental package is enclosed within a drag shield suspended at top of drop area by highly stressed music wire.

- The drag shield has high ratio of weight to frontal area and low drag coefficient.

- The double-acting air cylinder with hard steel knife attached to piston, backed by an anvil, cuts stressed wire to release package (no disturbances imparted to package).

- The experiment package and drag shield free fall independently of each other (air drag associated with relative motion of experiment the package is only acting force).

- Deceleration spikes on bottom of the drag shield penetrate the sand pit. (At impact the experiment package has traversed vertical distance within the drag shield.)

- The maximum drop frequency is eight drops per day.

5.18-Second zero gravity facility: A schematic of the zero-gravity facility is shown in figure 9; specifications and characteristics are given in table VI; and its mode of operation is given below:

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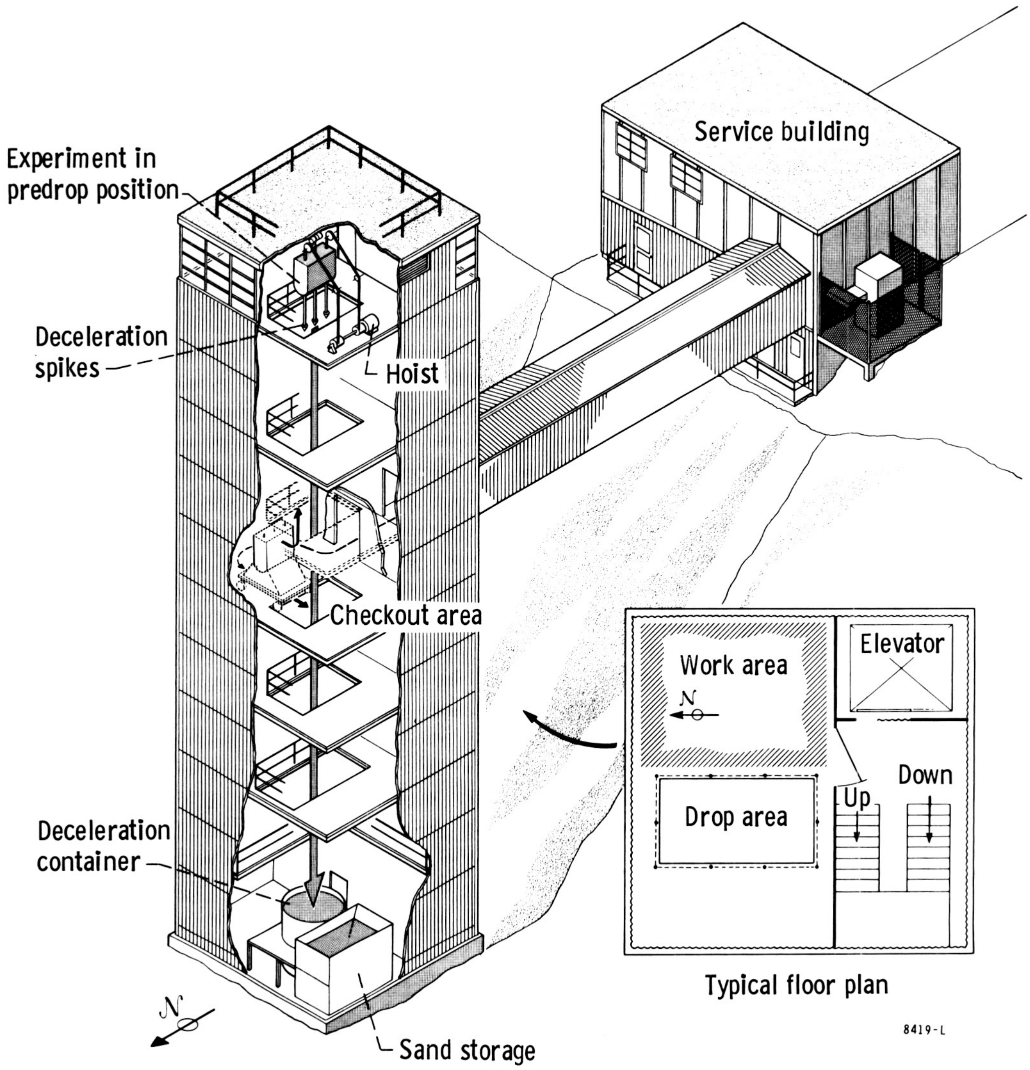


FIGURE 8. - LEWIS 2.2-SECOND ZERO-GRAVITY FACILITY (DROP TOWER).

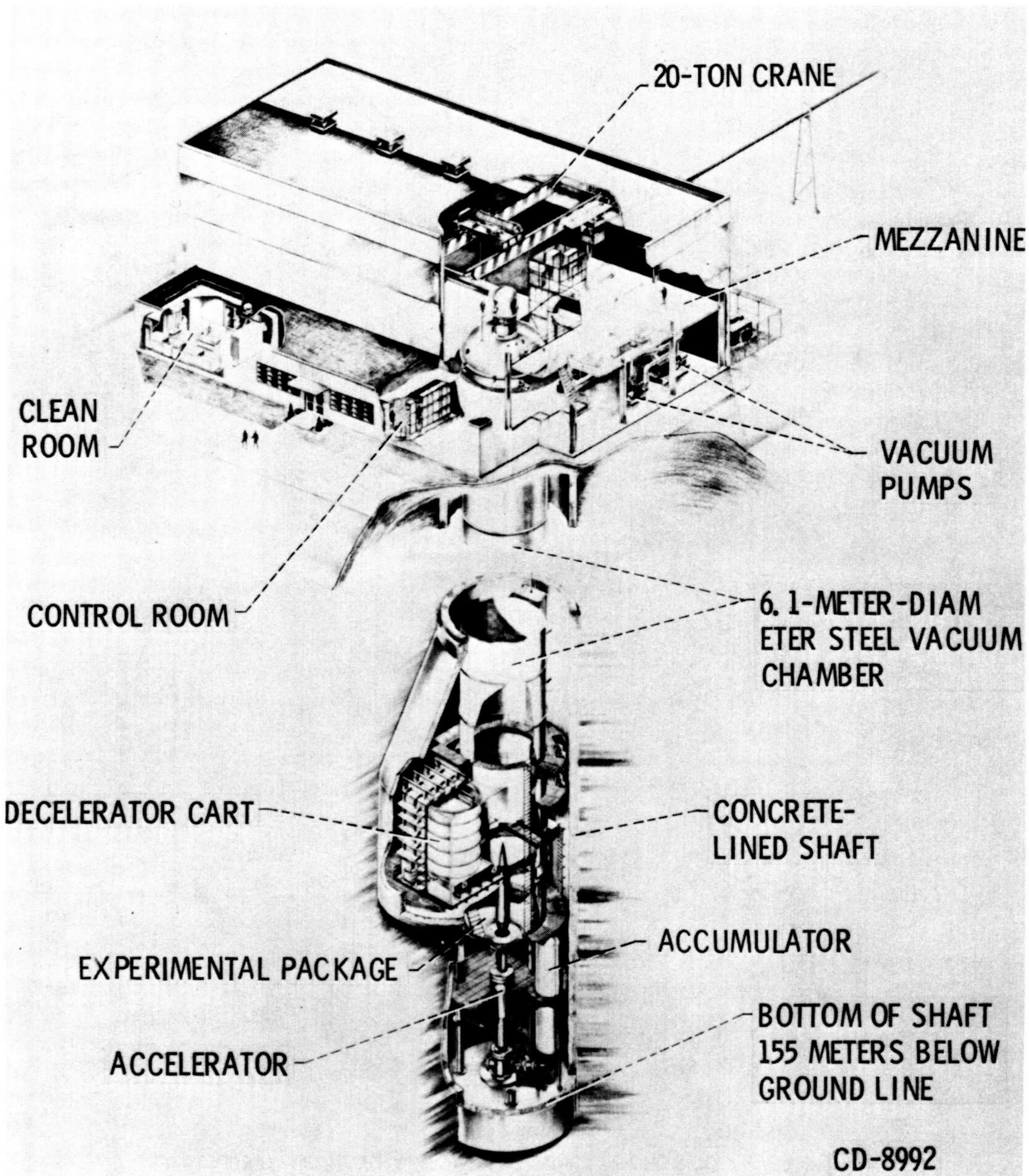


FIGURE 9. - LEWIS 5.18-SECOND ZERO-GRAVITY FACILITY.

- The experiment vehicle is suspended by a support shaft on a hinged-plate release mechanism in the top of the vacuum chamber.

- Before the drop, power is supplied from ground equipment through umbilical attached to the top of support shaft.

- The vacuum chamber is pumped down to 10^{-2} torr.

- The experiment vehicle is released by pneumatically shearing a bolt that holds the hinge in the closed position

- A closed-circuit television monitors the trajectory and deceleration.

- The package is decelerated by a cartful of small expanded polystyrene pellets.

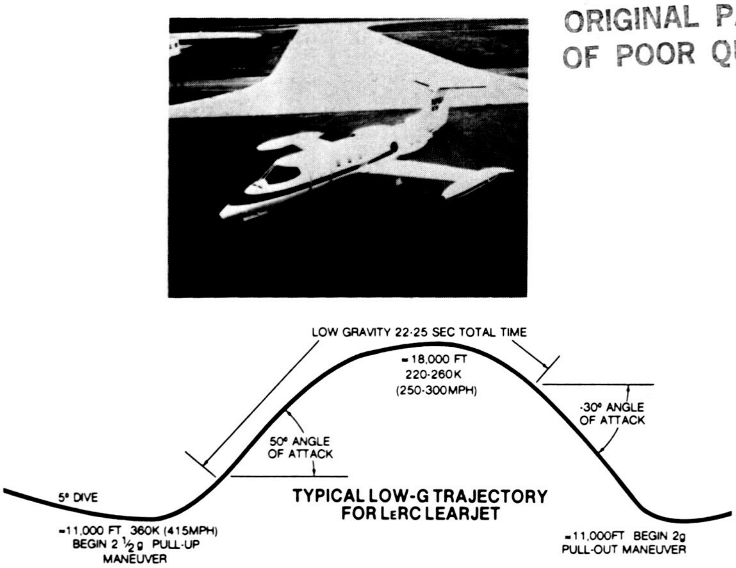
Lewis model 25 Learjet: A typical low-g trajectory for the LeRC Learjet is shown in figure 10. The dimensions of the interior of the fuselage are given in figures 11 to 13. The specifications and characteristics of the aircraft are presented in table VII.

Johnson Space Center KC-135 aircraft: The interior dimensions are given in figures 14 to 17. The specifications and characteristics of the KC-135 aircraft are given in table VIII.

TABLE V. - 2.2-SECOND DROP TOWER SPECIFICATIONS AND CHARACTERISTICS

Drop rig dimensions (LWH):	
Length	91.4 cm (36 in.)
Width	40.6 cm (16 in.)
Height	74.9 cm (29.5 in.)
Drag shield dimentions:	
Length	101.6 cm (40 in.)
Width	50.8 cm (20 in.)
Height	137.2 cm (54 in.)
Drop rig weight	
Drag shield	331 kg (730 lb)
Drop rig	34 kg (75 lb)
Experiment[a] (variable)	70 kg (155 lb)
Operational parameters	
Drop height	27 m (89 ft)
Microgravity (free fall) duration	up to 2.2 sec
Deceleration rate	15 to 20 g's
Data acquisition	
Milliken high-speed motion picture camera:	
Fixed speed	400 frames/sec
Variable speed	12 to 400 frames/sec
Film	Eastman Ektachrome video news high-speed 7250 tungsten (16 mm)
Data acquisition and control	
Tattletale model IV	
Number of analog inputs	11
PC communication	
Number of input-output ports	16
Data rates	23 to 238 (readings/channel)/sec
Memory	32K to 512K
Programming language	Basic
Power availability (battery)	
Type	Gates lead-acid "x" cells
Capacity rating	5 A hr
Nominal cell voltage	2.0 V
Peak power rating at 200 A	200 W
Standard battery pack	14 batteries/28 V
Conversion capability	dc to dc

[a]Currently heaviest.



FOR USE IN DEVELOPMENT OF SPACE-EXPERIMENT HARDWARE

- DETERMINE USEABILITY OF HARDWARE COMPONENTS
- SCREENING OF PROPOSED EXPERIMENTAL TECHNIQUES
- PRE-LAUNCH TESTING OF COMPLETE EXPERIMENTS

FIGURE 10. - LEWIS MODEL 25 LEARJET.

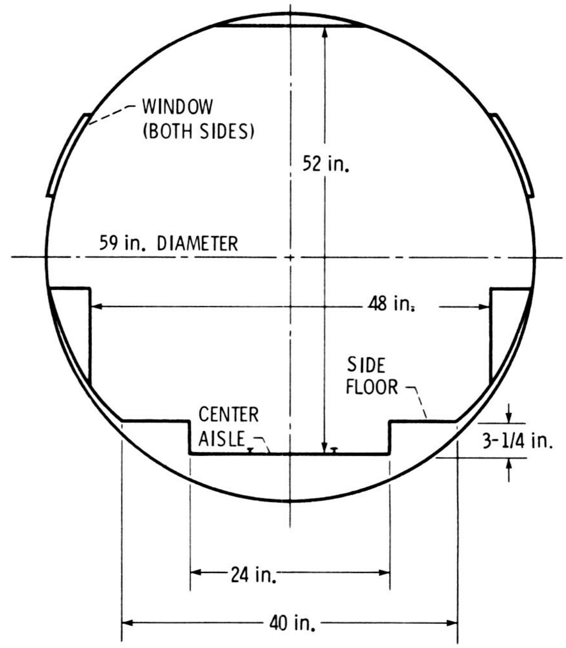


FIGURE 11. - CROSS SECTION OF LEWIS LEARJET FUSELAGE.

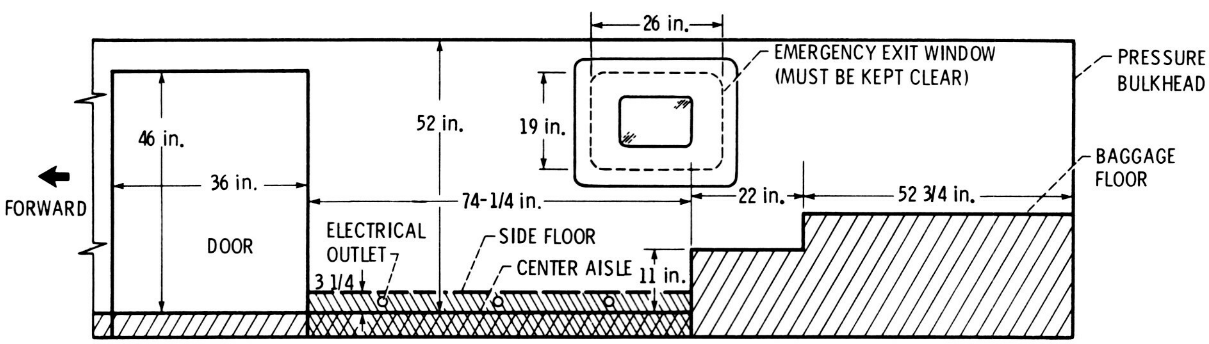


FIGURE 12. - ELEVATION VIEWS OF LEWIS LEARJET FUSELAGE.

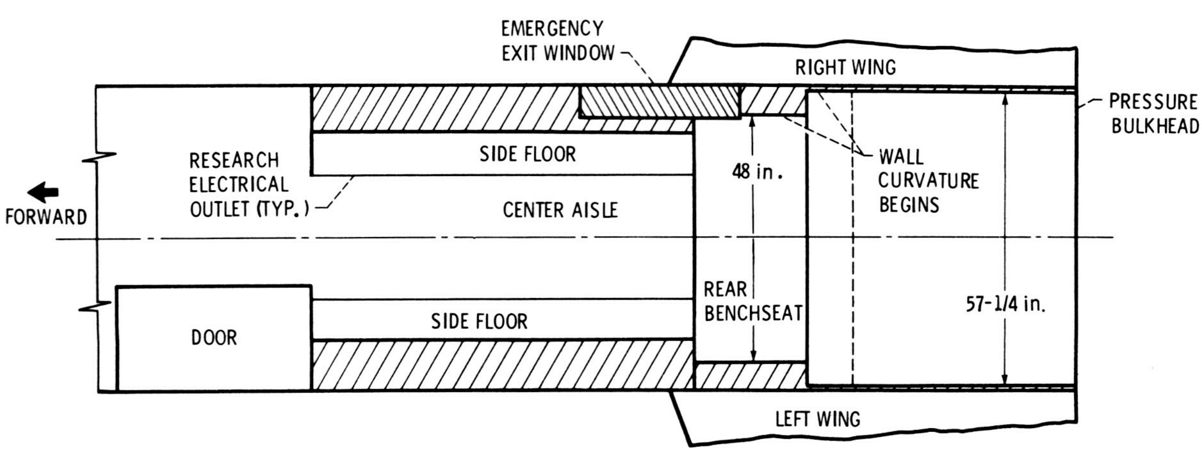


FIGURE 13. - PLAN VIEW INTERIOR OF LEWIS LEARJET FUSELAGE.

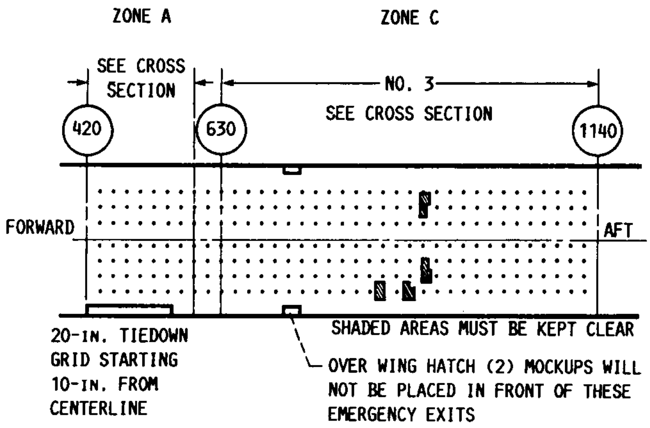


FIGURE 14. - TOP VIEW OF KC-135A NASA 930.

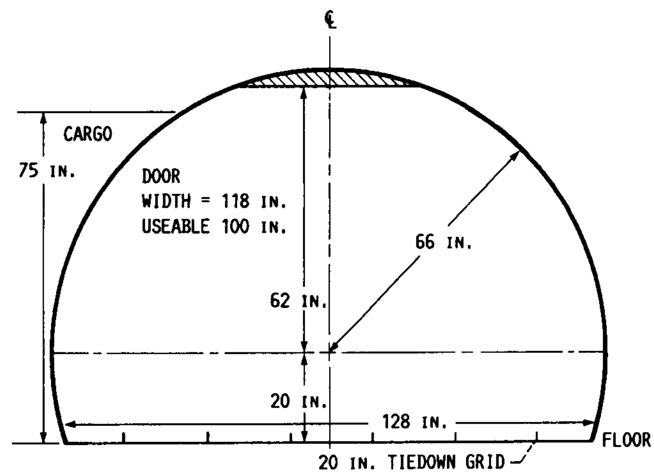


FIGURE 15. - ZONE A CROSS SECTION LOOKING FORWARD IN KC-135.

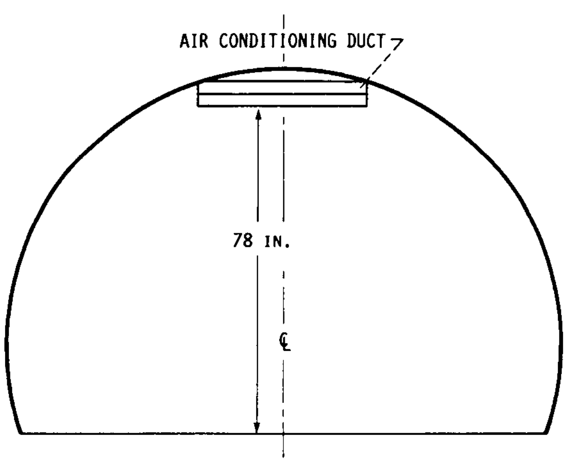


FIGURE 16. - ZONE B CROSS SECTION LOOKING FORWARD IN KC-135.

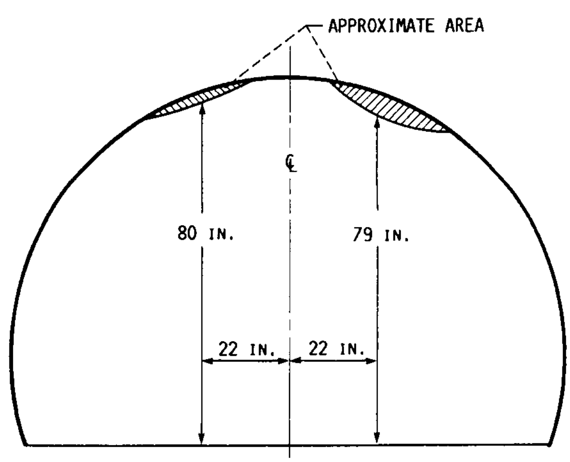


FIGURE 17. - ZONE C CROSS SECTION LOOKING FORWARD IN KC-135.

TABLE VI. - 5.18 SECOND ZERO GRAVITY FACILITY SPECIFICATION/CHARACTERISTICS

Drop height	130 m (430 ft)
Vacuum chamber diameter	6.1 m (20 ft)
Gravitational acceleration[a]	10^{-5}g for 5.18 sec
Deceleration rate[b]	up to 35g's
Experiment vehicle (cylindrical):	
External dimensions	1 m diam. by 3.4 m high
Experiment volume	1 m diam. by 1.5 m high
Flexibility	per experiment
Experiment hardware mass	<230 kg
Operational parameters:	
Drop height	130 m
Microgravity duration	5.18 sec
Deceleration rate	35g's
Data acquisition:	
Camera	Milliken high-speed motion picture
Fixed speed	400 frames/sec
Variable speed	12 to 400 frames/sec
Film	Kodak Ektachrome video news SO-251 Estarbase
Data acquisition and control system:	
Currently being updated	
Telemetry	
Power availability	(same as for 2.2-Second Drop Tower)

[a]At chamber pressure of 10^{-2} torr
[b]Retrieval in expanded polystrene pellets.

TABLE VII. - LEWIS MODEL 25 LEARJET: SPECIFICATIONS/CHARACTERISTICS

Flight research instrument rack (two can be mounted)	
Dimensions (L W H)	60.9 by 52.7 by 90.8 cm
Stress limits	
Weight	84.6 kg
Turning moment	3272 in.-lb (369 nm)
Flexibility	
Operational parameters	
pull up	2g to 2.5g
Microgravity acceleration at 10^{-2}g	15 to 20 sec
Number of maneuvers per flight	6
Data acquisition:	
High-speed photography	
Three-axis servoaccelerometers	
Flukes:	
High speed	32 channels, 1000 counts/sec
Low speed	22 channels
Power availability (maximum currents):	
At 28 V dc	80 A
At 110 V/60 Hz	8.6 A
At 110 V/400 Hz	21.7 A

TABLE VIII. - KC-135 AIRCRAFT: SPECIFICATIONS/CHARACTERISTICS

Cabinet dimensions:	
Length	60 ft
Cross sections vary in dimension (see figs. 14 to 17)	
Cabinet environment:	
Pressure at sea level	14.7 psia
Pressure at 11 000 ft	9.7 psia
Loss of pressure	2.7 psia
Temperature	50 to 80 °F
Electrical power:	
At 28 Volt dc	80 A
At 110 Volt ac, 400 Hz, single phase	50 A
At 110 Volt ac, 400 Hz, three phase	50 A/phase
At 110 Volt ac, 60 Hz, single phase	20 A

Space shuttle/station accommodations. - The accommodations aboard the space shuttle and the space station were presented by Robert Stubbs. The orbiter of the National Space Transportation System (NSTS) is pictured in figure 18 and shows the various carrier locations for conducting space experiments. Table IX lists the carriers and their accommodations. Figure 19 shows cutaway views of the flight deck and the middeck. The latter location, or the crew's quarters, can be used as a location for conducting experiments. Figure 20 displays the middeck accommodations for microgravity experimentation. Crew involvement in the experiment is an advantage in utilizing the middeck area.

Small self-contained payloads can be flown aboard the space shuttle via get away special canisters (GAS Cans) located in the shuttle bay (see fig. 21). The spacelab consists of the laboratory module and open pallets (see fig. 18). The laboratory module provides a shirt-sleeve environment for the crew to operate instruments and perform experiments. A tunnel provides access between the orbiter middeck and the module. The pallets are large, open platforms designed to support instruments and experiments that are amenable to or require direct exposure to space. Up to five pallets can be flown without the laboratory module, three pallets can be flown with a short module and two pallets with a long module. For pallets-only configurations key data and power control subsystem elements are housed in a large canister, called the igloo, that provides a pressurized and thermally controlled environment for them. The igloo, and the remaining essential subsystem elements mount to the front frame of the first pallet.

The Hitchhiker carriers provide access to space for users who need more services and/or volume and weight than can be provided by GAS cans but do not need all of the capabilities offered by the pallets. Hitchhiker-G is a side-mounted bay carrier and Hitchhiker-M is an across-the-bay carrier. The Spartan is a free-flying carrier developed to accommodate instruments from the Pointed Sounding Rocket Program. It rides into orbit on a bridge structure before being released to conduct its observing program and is later recaptured by the shuttle. To date there are no RF links with Spartan so all maneuvers are preprogrammed using its attitude control system.

TABLE IX. - CURRENT NSTS CARRIERS

Carrier	Carrier weight, lb	Carrier provided services					
		Experiment weight, lb	Power[a],		Cooling (passive/ active)	Data (recording/ downlink)	Commands (onboard/ uplink)
			DC, W	AC, VA			
NASA							
Middeck	N/A	120	115	None	P	None	None
Large GAS can	[b]170	200	None	None	P	None	0
Spartan	~4000	500	200	None	P	R	0
Hitchhiker-G	700	700	1300	None	P	D	0/U
Hitchhiker-M	-----	1 140	1176	None	P	D	0/U
MDM pallet	~2200	6 800	1150	110	P/A	D	0/U
Enhanced MDM pallet	~2200	6 900	1000	110	P/A	D	0/U
Step pallet	~2200	6 020	500	110	P/A	R/D	0/U
Igloo pallet	~6250	10 230	3600	2000	P/A	R/D	0/U
Igloo-IPS pallet	~8800	5 930	2600	2000	P/A	R/D	0/U

[a]Power may not be provided continuously at this level daily energy prodived is limited and negotiable.
[b]Does not include weight of GAS beam or bridge assembly.

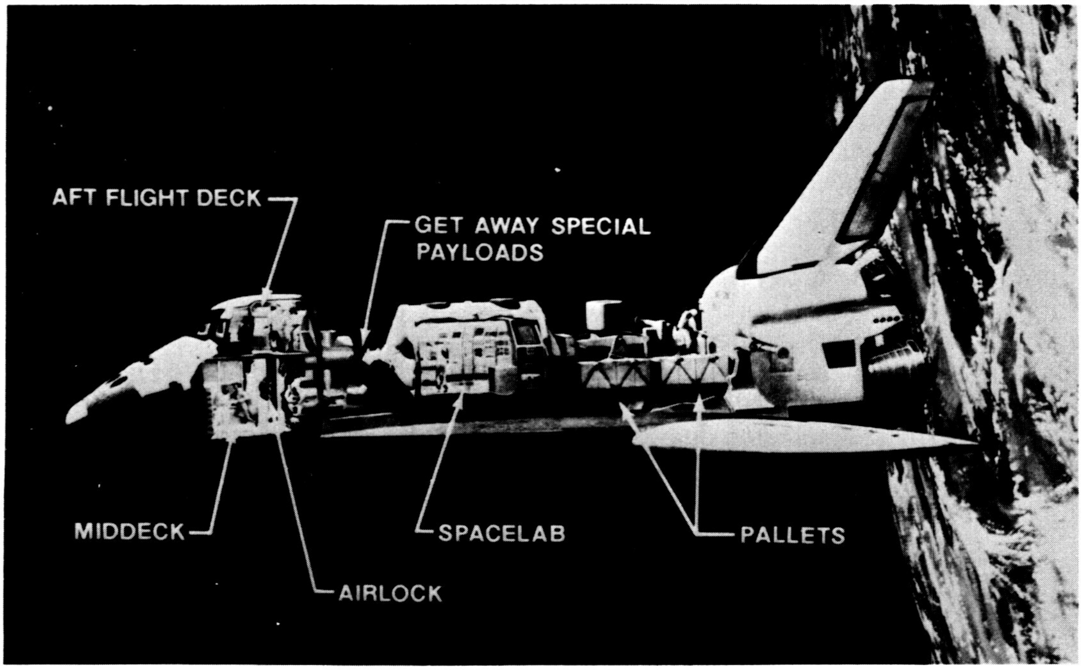


FIGURE 18. - THE NSTS ORBITER.

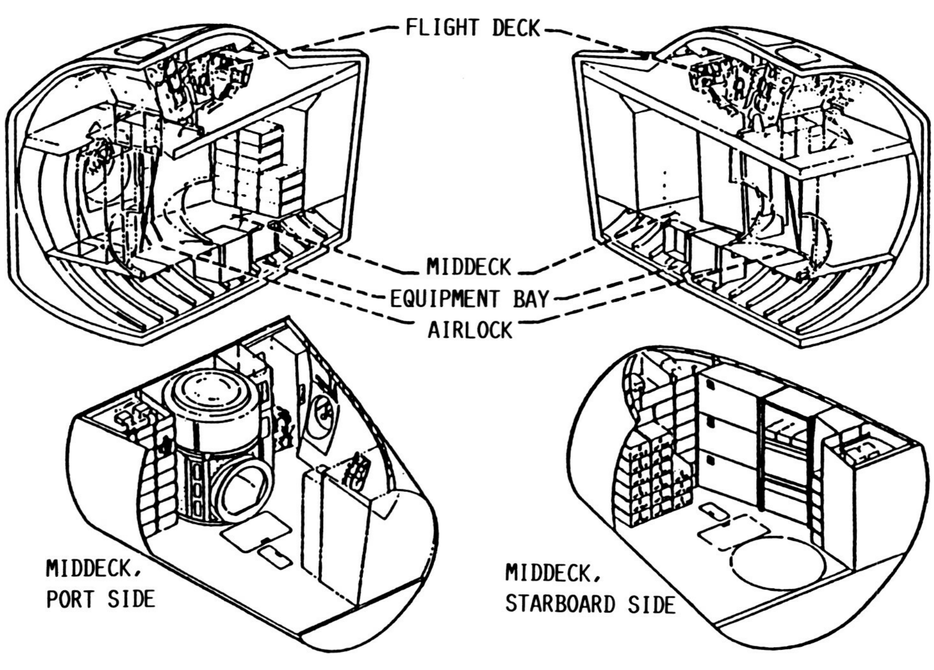


FIGURE 19. - ORBITER CREW CABIN ARRANGEMENT.

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MIDDECK LOCKER

SIZE	10 X 17 X 20 INCHES
WEIGHT CAPABILITY	~50 POUNDS

MIDDECK CANISTER

SIZE	17" DIA X 20" LENGTH
WEIGHT CAPABILITY	~100 POUNDS

MIDDECK ELECTRONICS MODULE AVAILABLE

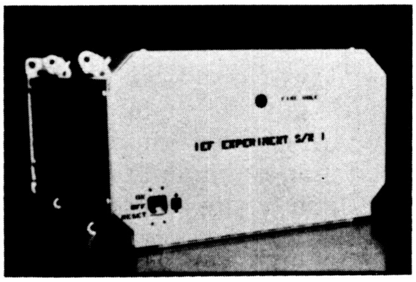
MIDDECK RESOURCES

POWER	280 W DC/600 W AC
COOLING	CABIN AIR
CREW INVOLVEMENT	

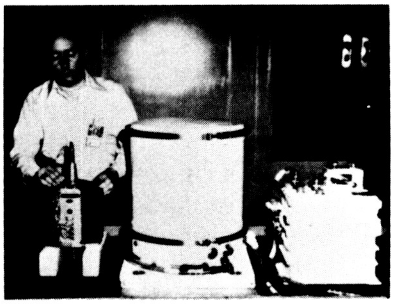
MIDDECK GALLEY

WEIGHT CAPABILITY	300 POUNDS
COOLING	WATER LOOP

THE MIDDECK



A MIDDECK LOCKER EXPERIMENT



A MIDDECK CANISTER EXPERIMENT

FIGURE 20. - ORBITER MIDDECK.

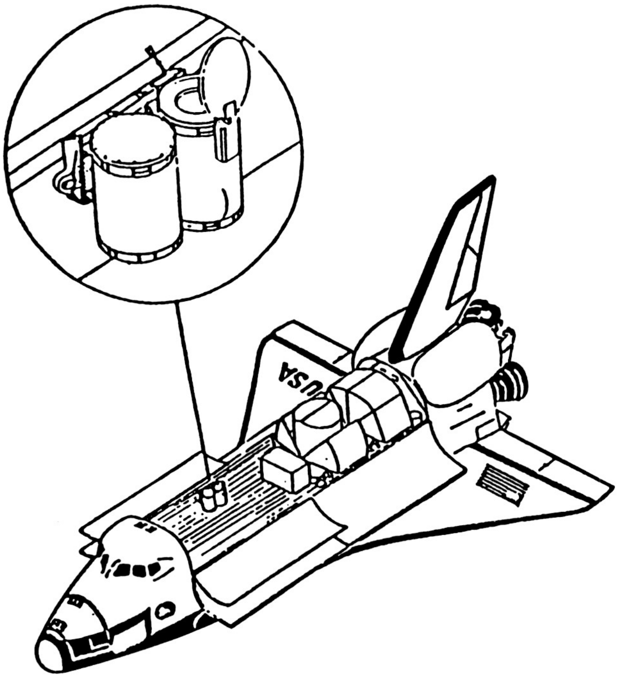


FIGURE 21. - EXAMPLE GETAWAY SPECIAL.

The Material Science Laboratory (MSL) is a dedicated discipline carrier system intended to meet the need of the material science community for a low-cost, quick-reaction carrier system that is especially adapted for large, heavy payloads. The MSL carrier provides power, experiment control, heat rejection, a low-g accelerometer, and data recording to a maximum of three experiment apparatus. An experiment may be operated by crew members using a control panel in the shuttle aft flight deck, by the investigator who can uplink commands from the ground, or by automatic programmed commands. The MSL and its support structure, the mission peculiar equipment support structure (MPESS), occupies one fourth of the shuttle payload bay. The weight is 308.4 kg per experiment, if three are flown, or a total weight of 925.3 kg for all experiments. Operational parameters given in table X.

The initial configuration of the space station, as shown in figure 22, is distinguished by its single horizontal boom, centrally located modules and solar panels near the ends of the boom. The direction of flight is also indicated. The enhanced version, shown in figure 23, features dual keels (for better vibration control), and solar dynamic power has been added to supplement the photovoltaic solar panels. There are four modules, each with shirt-sleeve environment, planned in the initial configuration (see fig. 24). The U.S. laboratory (USL) module is the forward starboard of the four modules; the U.S. habitation module is the forward port module; the rear starboard is the European or Columbus module; and the fourth or rear port module is the Japanese module called JEM. A representative outfitted USL is shown in figure 25, and figures 26 to 28 give the dimensions of the USL module and the dimensions of the single and double racks within the module. There is room along each wall for 11 double racks or 22 single racks. There is the capability of having racks in the floor and ceiling, but this space will probably be used for storage and subsystem equipment. The electric power accommodations for the USL and other accommodations are given in table XI.

Figure 29 illustrates the gravity gradient at the space station. Note that the gradient in the vertical direction is three times that in the horizontal direction. Finally, figure 30 displays the station module placement with respect to the center of gravity.

Fluid experiment system experience. - The planners of the workshop thought the participants would benefit from a presentation of an actual space experiment using laser diagnostics. But no U.S. combustion experiment employing laser diagnostics has been flown as yet. In fact the only U.S. combustion experiment conducted in space to date was aboard Skylab 4 in February 4 and 5, 1974 (Final Report Skylab Experiment M-479 Zero Gravity Flammability, J.H. Kimzey, JSC 22293, August 1986). The diagnostics for this experiment consisted of visual observation and 16-mm motion pictures taken at 24 frames per second. Thus we decided to refer to a fluids flight test to illustrate a laser

TABLE X. - MATERIAL SCIENCE LABORTORY OPERATIONAL PARAMETERS

Power:	
For all MSL payloads:	
Peak	2595 W
Continuous	1410 W
For each of three experiments:	
Peak	865 W
Continuous	470 W
Energy (for each of three experiments)	32.1 kWh
Voltage:	28 4 V dc
Data handling:	16 kbps

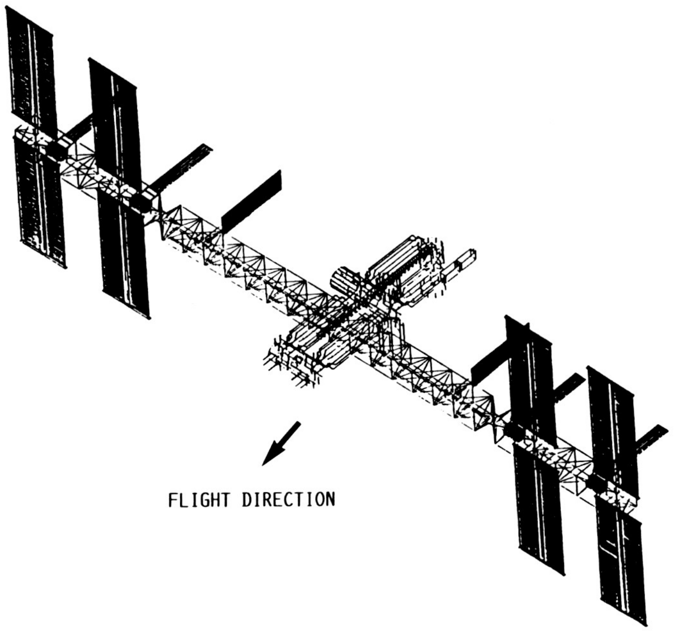


FIGURE 22. - INITIAL CONFIGURATION OF SPACE STATION.

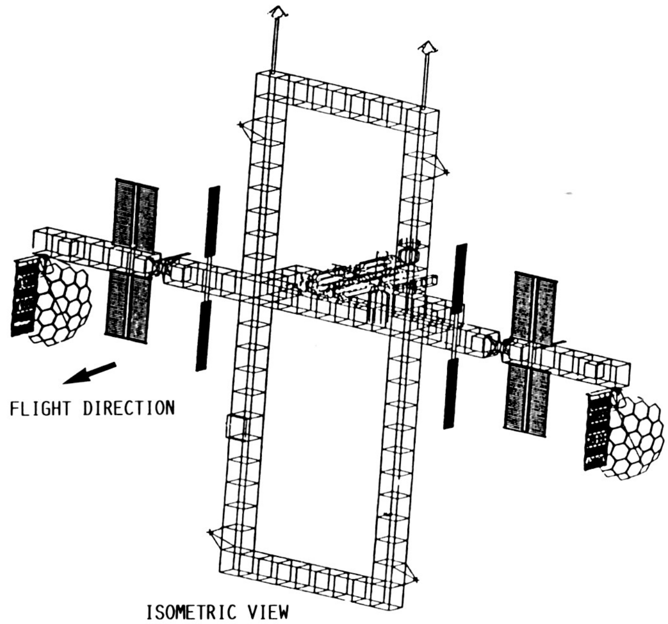


FIGURE 23. - ENHANCED CONFIGURATION OF SPACE STATION.

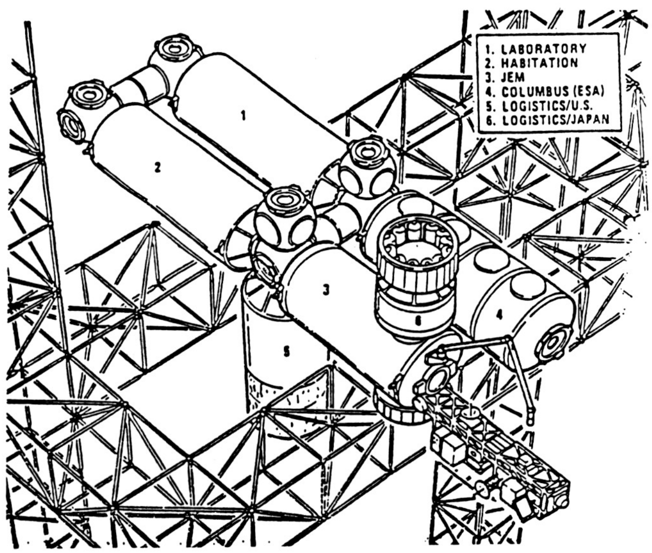


FIGURE 24. - SPACE STATION INITIAL OPERATING CONFIGURATION (MODULE ASSEMBLY).

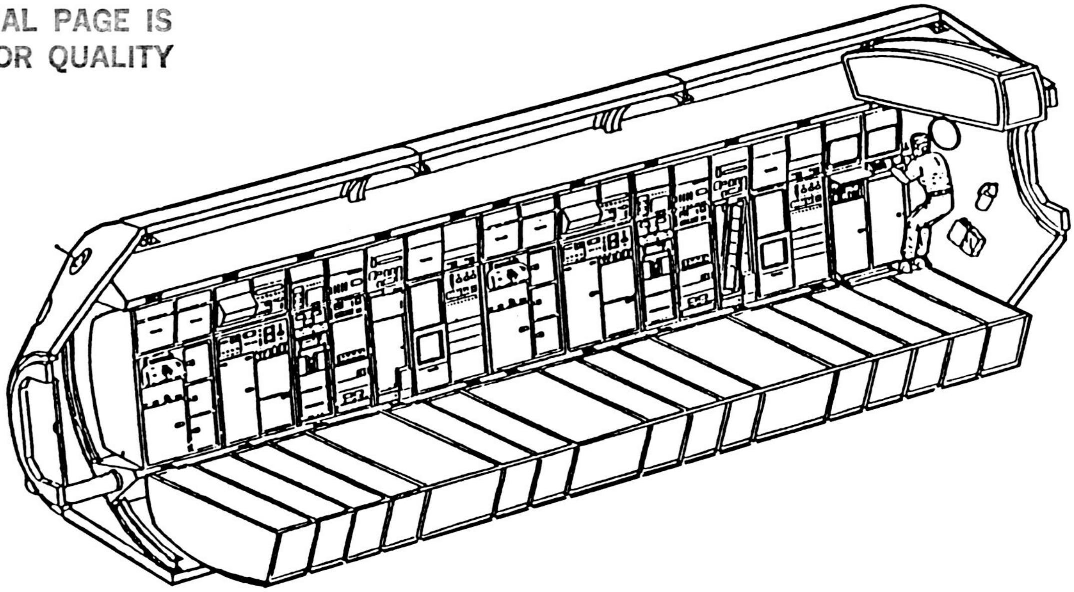
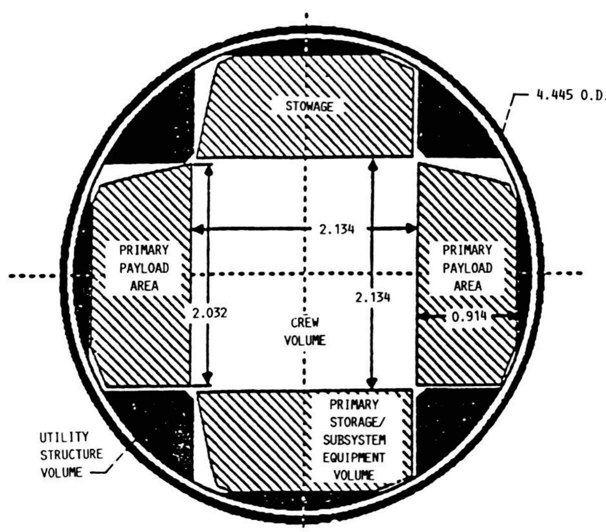
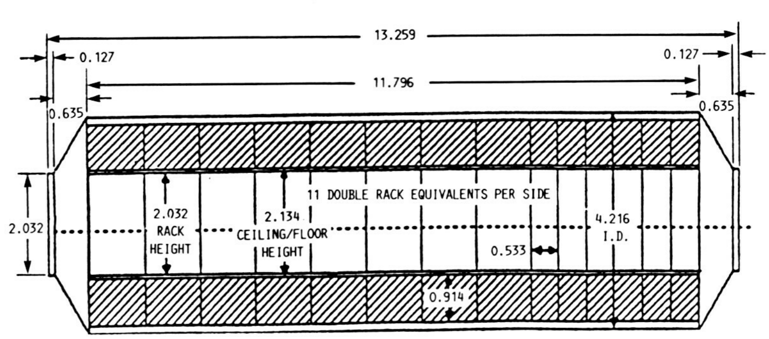


FIGURE 25. - REPRESENTATIVE OUTFITTED USL.



(a) CROSS SECTION.



(b) SIDE VIEW.

FIGURE 26. - USL FOUR-STANDOFF CONFIGURATION. (DIMENSIONS ARE IN METERS.)

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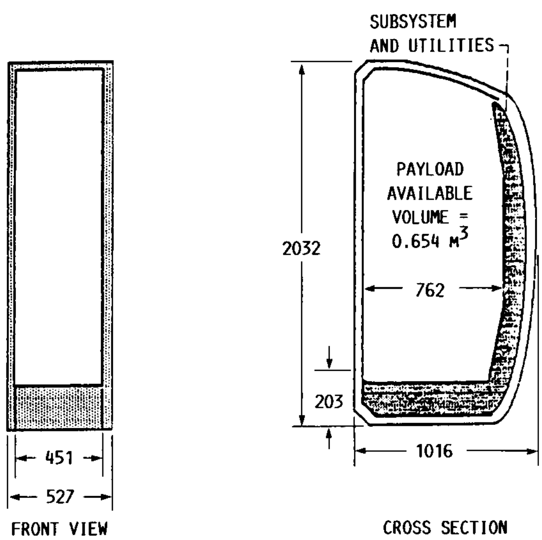

FIGURE 27. - SINGLE RACK VOLUME. (DIMENSIONS ARE IN MILLIMETERS.)

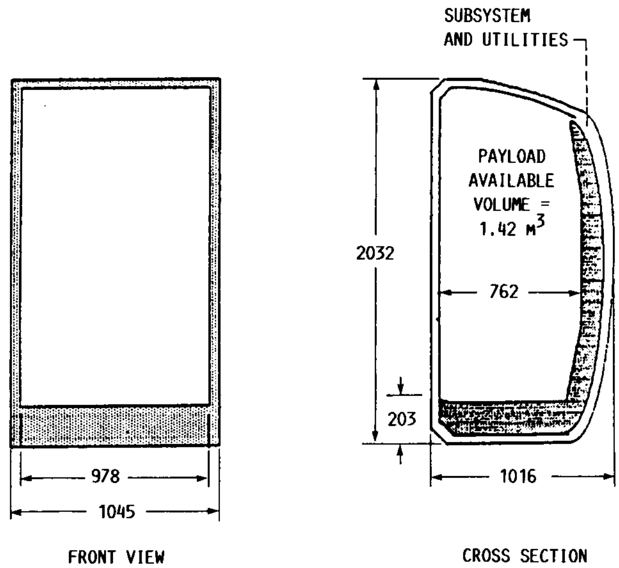

FIGURE 28. - DOUBLE RACK VOLUME. (DIMENSIONS ARE IN MILLIMETERS.)

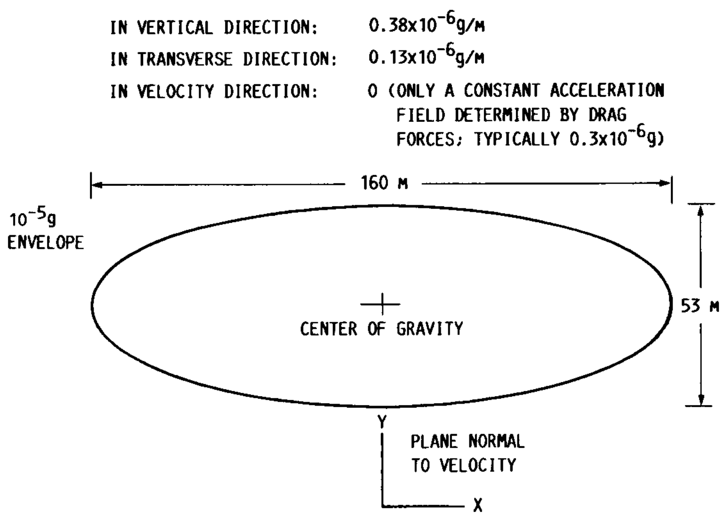

FIGURE 29. - GRAVITY GRADIENT AT SPACE STATION.

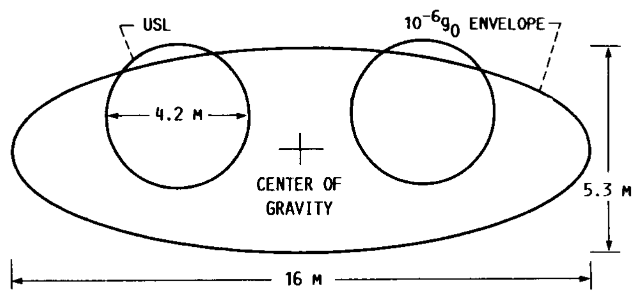

FIGURE 30. - SPACE STATION MODULE PLACEMENT WITH RESPECT TO CENTER OF GRAVITY.

TABLE XI. - ACCOMMODATIONS FOR USL

Power:	
Available for users	50 kW
Number of 50-kW power distribution systems	Two (redundant)
Available at six double-rack locations	15 kW
Single-phase power delivered to all modules	208-V, 20-Hz
Conversion capability to	60 kHz, 120/208 V ac, and 28 V dc
Heat rejection	
Provided by water cooling system	
For USL	50 kW
For users	25 kW
Additional cooling provided by consumable cryogenics	
Vacuum/waste removal:	
Vacuum pressure supplied to each rack[a] via 6-in. pipe	1 mtorr
Closed waste system, gasses pumped (or compressed) and stored until periodic, controlled venting periods	
Accelerometer subsystems	
Monitor three-axis microgravity levels	
For frequencies <1 Hz	to 10^{-8}g
For frequencies from 1 to 50 Hz	to 10^{-7}g

[a]Lower pressures responsibility of users

diagnostic system operating in space. Ronald Porter from Marshall Space Flight Center shared his experience with the Fluid Experiment System (FES). In his presentation he emphasized generalized managerial and procedural aspects of flight hardware and flight experiments. For this report, however, the editors decided to concentrate on the problems associated with the diagnostics.

The fluid experiment system (FES) is a modular facility containing a multipurpose, multiuser holographic system for investigating fluid experiments in low gravity. A holographic system was chosen to maximize data collection and minimize the optical setup. The FES flew for the first time in May 1985, on Spacelab 3 for the investigation of triglycine sulfate (TGS) crystal growth. In addition to recording holograms, the FES provided real-time schlieren information to the ground-based experiment team. The laser used in the FES was a commercial 30-mW He-Ne laser. The wavelength of the beam is 632.8 nm in the TEM00 mode with the polarization vector in the vertical direction. The laser was hardened to launch vibrations by adding support to the plasma tube. The mirrors of the FES were made of BK-7 glass, a borosilicate crown with a refractive index of 1.5176. The mirrors had a 1/10 wavelength flatness and were coated with a multilayered dielectric film to provide maximum reflection at the 632.8 nm wavelength. The windows of the test cell were made of BK-7A1 glass and had a quarter wavelength flatness. The beam splitters of the FES were also made of BK-7A1 glass and had a flatness of 1/10 the wavelength. The primary axis of the FES was capable of resolving a feature of 20 μm in size. The transverse axis resolved a feature of 35 μm in size. The flight apparatus required a double rack space on the shuttle. This included the optical bench and the test cell preheat section. The electronics for both the FES and a companion experiment, the vapor growth crystal system (VCGS), are also included in the FES rack. Figure 31 shows the fluid experiment system rack assembly; figure 32, the light paths for constructing the holograms; and figure 33, the light path of the schlieren system used in the real-time video downlink.

Some problems were discovered in the FES during the first flight. There were difficulties in the schlieren system due to the gradient knife-edge and misalignment of the motorized knife-edge positioning mechanism. Another problems was the non-uniformity of the illumination of the film when constructing a hologram. All these

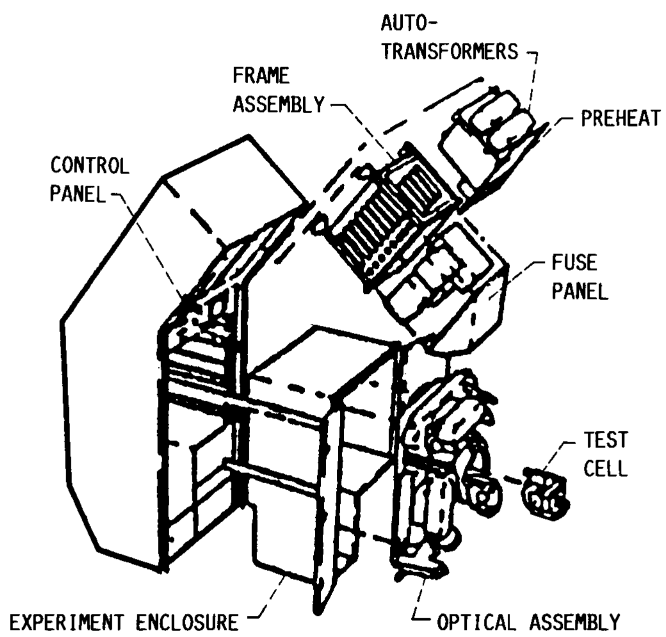

FIGURE 31. - FLUID EXPERIMENT SYSTEM RACK ASSEMBLY.

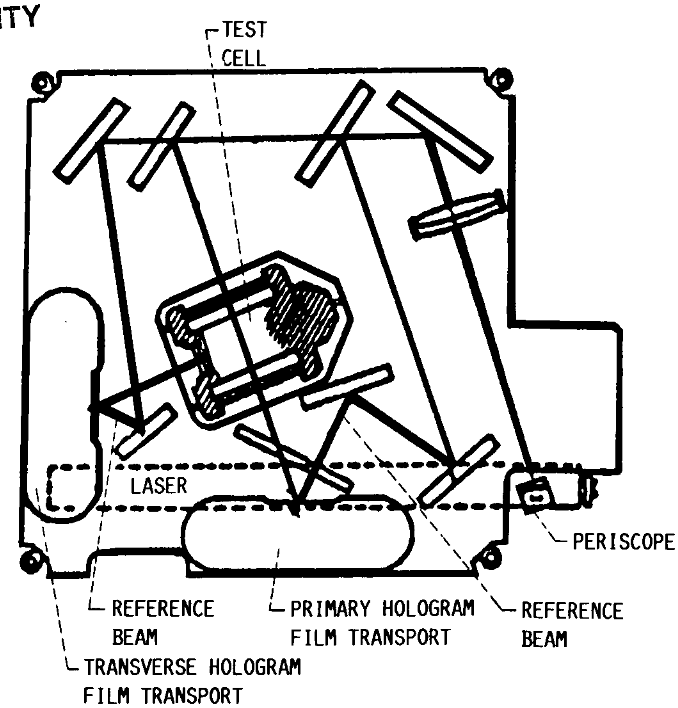

FIGURE 32. - LIGHT PATHS FOR CONSTRUCTING PRIMARY AXIS AND TRANSVERSE AXIS HOLOGRAMS IN THE FES.

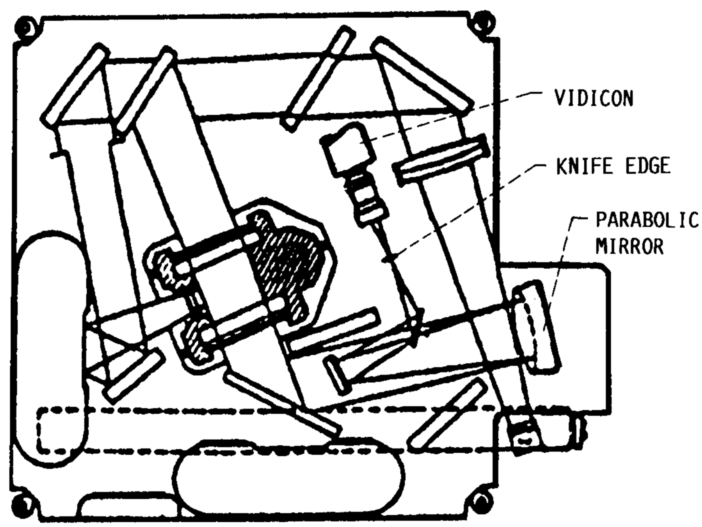

FIGURE 33. - LIGHT PATH OF THE SCHLIEREN SYSTEM THAT IS IN THE REAL-TIME VIDEO DOWNLINK.

TABLE XII. - AVAILABLE DIAGNOSTICS FOR MAJOR COMBUSTION PARAMETERS

Major combustion parameters	Available diagnostics
Temperature and temperature gradient	Thermocouples[a], laser thermometry
Velocity	Flowmeters[a], Δp standard orifice[a], LDV, particle image velocimetry (PIV)
Species:	
Stables	Gas chromatograph, mass spectrometer, LIF
Radicals	LIF
Radiation	Radiometer[a]
Pressure	Transducers[a]

[a]Requiring no substantial development for microgravity applications.

problems have since been resolved. For further information on the FES, like the holographic reconstruction techniques, see the paper by William K. Witherow, "Reconstruction Techniques of Holograms From Spacelab 3", Applied Optics, vol. 26, no. 12, June 15, 1987.

Microgravity Combustion Diagnostics Program Review. - Gilbert Santoro reviewed the MCD project status, which was in its planning stage. As stated in the Introduction, MCD is part the Advanced Technology Development (ATD) program out of the Microgravity Science and Applications Division at NASA Headquarters to enable the development of future microgravity science and applications experimental hardware and to enhance the scientific integrity and yield of space flight experiments. Also discussed in the Introduction was the objective and approach of the MCD ATD project and the purpose of the MCD Workshop. As was stated earlier in the discussion of the combustion experiment aboard Skylab 4, the diagnostics were limited to film and human observations. The diagnostics for combustion experiments in space, as well as those ground-based low gravity experiments, are currently limited to film or videotape and thermocouples. We would like to use advanced diagnostic techniques for low-gravity combustion experiments, ground-based and space, to better verify the modeling of combustion processes. The measuring instruments now being used will not fully provide the data required for verification testing. The rationale for emphasizing laser techniques during this workshop can be explained by table XII, where the major combustion parameters are cited with the available diagnostics.

Those diagnostics requiring no substantial development for microgravity applications are noted. The diagnostics that do require development for low-gravity applications are the various laser techniques, gas chromatography, and mass spectrometry. The advantages of laser diagnostics for combustion testing are that the methods are nonintrusive and nonperturbing; have high-temperature capability; and are fast, spatially precise, unambiguous, and versatile. There are, of course, some disadvantages. Optical access is required, the methods are expensive, signal strengths are low, and the signals are subject to various forms of interference. In addition, large data acquisition and processing requirements frequently arise. From this discussion it is expected that laser techniques will be a major contributor to the diagnostic systems developed for combustion experiments conducted aboard the space shuttle and later aboard the space station.

Microgravity science requirements review. - Essential in any discussion of diagnostics would be a list of science requirements for the experiments under consideration, that is parameters to be measured and their ranges, accuracies, and spatial and temporal resolutions. The science requirements for the microgravity combustion experiments were generated from the general classes of such experiments as they are presently visualized see list below:

- Premixed gases (tubes and bomb)
- Gas diffusion flames
- Solid surfaces (with and without imposed flows)
- Droplets and fuel sprays
- Pools and films (preignition mechanisms and flame spread)
- Particulate clouds
- Material ignition studies
- Smoldering

Kurt Sacksteder presented the science requirements for these classes of experiments, but as a wish list, that is, as specifications for the parameters as experimentalists and theoreticians would like to have them rather than as a list of presently achievable values. The diagnosticians unanimously objected to this format and stated their desire to work with a list of minimally useful values. In fact, the idealized procedure from the point of view of the diagnosticians would be to have the minimum science requirements of each specific test. Then the appropriate calculations could be made and recommendations as to the choice of diagnostics could be given. But the purpose of the workshop was not to solicit advice on specific experiments; rather, the purpose was to seek direction on what diagnostic development programs to support in order to enhance the quality of the data from space combustion experiments. For the purpose of this report a revised set of the science requirements was generated to represent a summary set of practical values covering the entire list of combustion classes. These revised requirements are presented in table XIII.

TABLE XIII. - COMBUSTION SCIENCE REQUIREMENTS FOR THE FLUIDS AND COMBUSTION DIAGNOSTICS ADVANCED TECHNOLOGY DEVELOPMENT PROGRAM

[November 10, 1987.]

	Range	Accuracy, percent	Spatial resolution, mm	Sampling frequency, Hz
Temperature:				
Gas Phase	300 - 3000 K	[a]5	5	100
Bulk solid	270 - 400 K	1	10	50
Solid surface	270 - 800 K	5	5	50
Bulk liquid	270 - 400 K	1	10	25
Liquid surface	270 - 400 K	0.1	5	25
Pressure:				
Gas phase	10 - 500 kPa	1		25
Velocity:				
Gas phase	1 - 5000 mm/sec	5	1	25
Liquid phase	0.5 - 100 mm/sec	5	1	10
Species concentrations				
H_2O, CO_2, OH, CO, O_2, N_2, small HC's, halons	0 - 1 mole fraction	2	1	10

[a]The value represents the minimum of 10 K.

WORKING DISCUSSIONS

Microgravity Science Requirements Discussion

General philosophy regarding optical methods. - Given the severe constraints that accompany the microgravity environment, the question arose as to the emphasis on optical diagnostic techniques. Typically, laboratory systems for performing sophisticated optical diagnostics occupy large volumes, consume vast amount of electrical power, and require several experienced individuals to operate them. These attributes are undesirable from the standpoint of space-based measurement systems. There exist many well established techniques that are not based on optical methods and are indeed more straightforward to implement. But the primary motivation for emphasizing optical techniques is to provide measurements that are nonperturbing. This motivation arises, in general, from the presence of rather delicate force balances and often weak competing mechanisms that are become important to processes or phenomena in the absence of gravity. Conversely, it is certainly incumbent on the participants in the program to use the simplest possible method to provide them with the appropriate measurements. More conventional methods, such as temperature or gas sampling probes are being considered but are outside the charter of this particular discussion. It is worth noting that a ground-based optical diagnostic technique may have its primary utility in verifying the nonperturbing nature of a more conventional probe. In addition, it should be stated that not all optical methods have an a priori requirement for coherent sources (i.e., lasers).

General classes of microgravity combustion experiments. - The list of the experiment classifications (see Microgravity Science Requirements Review Section), was reintroduced for establishment of concurrence. The only stated opposition to this classification concerned the absence of turbulent processes. The relative importance of turbulence in the present context continues to be an issue for debate. At present no proposals have been submitted in this area. The prevalent attitude among combustion researchers at Lewis is that a systematic understanding of laminar processes will consume the current resources of the program for some time to come.

Measurement parameters of interest. - The following parameters are of dominant interest for the purpose of microgravity combustion diagnostics and are listed in order of decreasing importance:

- Temperature fields
- Species concentration fields
- Velocity fields
- Particle density and size distribution
- Pressure

The prioritization is relevant only in the average sense (averaged over many possible experiments) and may not correspond to the particular needs of any one experiment. Owing to the importance of capillary forces in the absence of gravitationally driven buoyant convection, surface tension was appended to the list. It is often a significant parameter in the investigation of droplet combustion and of critical importance in the study of liquid pools and thin films. Pressure measurements are not viewed as requiring substantial development efforts, since most processes under consideration are isobaric and conventional pressure measurement techniques are suitable for space applications.

Two important distinctions arise that have a substantial effect on the selection of a particular diagnostic technique and the subsequent design of the actual measurement system. The first of these involves the requirement for full-field measurements, or at least simultaneous multipoint measurements, versus single-point measurements.

Although it is certainly desirable to have knowledge of a particular quantity at all points in space and time, it is clearly unrealistic to expect this type of information. The ultimate decision regarding which scenario to adopt is influenced by many factors. Some of these factors are inherent to the particular phenomenon under investigation. If, for example, spatial or temporal correlation of a transient or, perhaps, irreproducible event is required, single-point measurements will not suffice. In contrast, a full-field measurement may not provide the required precision or may be unable to support the necessary data rate. This decision may also be affected by the current state of understanding of any given combustion process. Extremely accurate single-point measurements are seldom useful without a rudimentary knowledge of the overall geometry or rate of reaction. In many cases qualitative visualization of some type must be obtained first.

The second distinction is between transient and steady-state processes. From an operational standpoint, the microgravity environment poses certain restrictions that can become important considerations. Those constraints may also affect the desire for multipoint measurements, as mentioned above. In a space flight experiment, one seldom has the luxury of executing many tests or tests of long duration while data are accumulated. Supplies of expendable reactants, electrical power, or available dedicated manpower are usually limited. Thus, one must often compromise measurement precision with spatial or temporal yield.

While there is much interest regarding the formation and luminous emission from soot particles, it is felt that the initial emphasis should be placed on nonsooting systems. In many cases the formation of soot is thought to be relatively unaffected by the presence of gravity and serves to further complicate or degrade the optical measurement process. Techniques that are predicated on processes with relatively weak scattering cross sections (e.g., Rayleigh scattering) will be severely hampered by the much stronger Mie scattered signal. Elastic scattering processes such as Rayleigh scattering are particularly troublesome since there is no wavelength shift involved. It should be noted, however, that in certain types of material flammability testing, sooting is unavoidable. In some cases it may be possible to estimate temperatures via soot pyrometry.

Requirements for microgravity diagnostic systems. - The nature of the space flight environment and its inherent severities uniquely constrains the design of experimental hardware. The following list of attributes is invariably essential for microgravity science applications:

- Compact
- Low power
- Forced cooling
- Reliability/durability
- Simplicity (autonomy)
- Modularity
- High spatial/temporal yield
- Safety

It should be recognized at the outset that certain quantities listed above have specifically defined ranges or tolerances, while others may be vaguely defined at present. For example, safety requirements are exceedingly well defined and are not likely to undergo major alterations. Amounts of available electrical power and physical space continue to be the subjects of on-going discussion, but rough approximations are currently available. The degree of modularity or automated operation that is ultimately desired, however, has not yet been determined and is an appropriate issue for development in the context of this particular program. A more detailed discussion of these considerations can be found in the section on the discussion of the recommended long-term effort.

Preliminary description of microgravity combustion science requirements. - To initiate discussions within the working group, workshop organizers presented a generic science requirements document. There are several factors which cause the task of composing such a document to be quite difficult. Most outstanding among these factors is the breadth of the subject matter under consideration. As we have seen in the preceding sections, there is a wide range of processes and phenomena of interest from the standpoint of fundamental microgravity science and the associated areas of application, such as spacecraft fire safety. Each respective area carries with it its own particular parameters of interest. The ranges and required accuracies of these parameters are affected not only by the inherent physics of the specific system but also by the present level of understanding. Since microgravity establishes an environment for science which is in many respects still in its infancy, often qualitative observations and coarse quantitative characterizations are lacking. It is virtually impossible in most cases to predict what this level of understanding will be at that future point when this diagnostic hardware will be used.

Of equal difficulty is the task of ranking the importance of specific experiments or sequences of experiments. The availability of flight opportunities currently is outpaced by the number of experiments posed by investigators, and this situation is expected to become more severe with time. The myriad considerations which influence these programmatic decisions tend to minimize the actual effect that the scientific community has on these matters. The ability of a diagnostic system to serve a variety of experimental endeavors in itself becomes one such consideration. While no single instrument will be applicable to all circumstances, the attempt to maximize its utility is very important.

Also difficult to appraise are certain areas of on-going technical development. An illustrative example of such an area is the development of new laser sources. The majority of diagnostics currently found in the laboratory use laser sources that are not flight compatible in their present form. Inordinate levels of power consumption, poor mechanical durability, large volume, and overall system complexity must all be addressed before usable flight hardware can be produced. Although this program has been funded to support these types of developmental issues, it is unrealistic to expect that such a program can support the development of all of the individual devices needed. A fundamental charter of this particular program is to stay abreast of the available device technologies, support their development in selected areas, and continually incorporate them as needed in an intelligent and systematic fashion.

The parameter ranges and accuracies that appear in the science requirements documents (see table XIII) were compiled from information supplied by the project scientists, project managers, and principal investigators currently participating in the microgravity combustion science program. As stated earlier, these data originally reflected desired measurements requirements although, in many cases, not technically realistic. The intent of this procedure was to force a compromise between the scientific investigators and the instrument designers so to provide systems of maximum utility for all concerned. The diagnosticians objected and stated their desire to work with a list of readily measurable data. The data in table XIII represent a step beyond present flight combustion experimental requirements, but they are are deemed realistic by today's technology.

Status of Combustion Diagnostic Capability

For the purpose of structuring the discussion of currently used diagnostic techniques, the primary measurement parameters were divided into three groups: (1) temperature and species concentrations, (2) velocity fields, and (3) particle densities and size distributions. Only the first and second categories were discussed in any detail. The various techniques which are generally used are listed for each respective category, and are shown in the list below:

I. Temperature and species concentration
   A. Scattering
      Raman
      Rayleigh
      Degenerative four way mixing (DFWM)
      Coherent anti-Stokes Raman scattering (CARS)
   B. Emissions
      Fluorescence
      Incandescence (pyrometry)
      Spontaneous
   C. Absorption
      Tuneable diode
      FTIR
   D. Index of refraction methods
      Interferometry
      Deflectometry
      (Multiple wavelength)
   E. Other

II. Velocities
   A. Requiring seed
      LDV and LTF
      Speckle
      Particle image methods
      Doppler Michelson
   B. Not requiring seed
      Photothermal deflection
      Fluorescence and multiphoton processes
      Doppler Raman

III. Particle density and size distribution
   A. Scattering
      MIE
      Phase Doppler
   B. Extinction

Temperature and species concentration. - For temperature and species concentration measurements, the primary considerations that pertain to scattering and emission (fluorescence) methods are the species specificity, the strength of the photon interaction process, and the source requirements.

Spontaneous Raman scattering is the most broadly applicable method, since virtually all species of interest are Raman active and are probed simultaneously. For systems involving complex chemistry, however, the analysis of the multicomponent spectra can be extremely involved. The wavelength shift associated with the inelasticity of the process is a benefit from the standpoint of stray light rejection and scattering from particulates, but fluorescence contributions can still pose a problem. The primary detriment of spontaneous Raman is the extreme weakness of the scattering process. This can, to a degree, be offset by using the inverse fourth power dependence on wavelength.

A major concern, however, is the availability in the future of flight compatible short wavelength or UV sources. The lack of compatibility will make the achievement of even point measurements difficult in space experiments and the extension to two dimensions extremely unrealistic for the present and perhaps for some time to come. Coherent anti-Stokes Raman scattering (CARS) has recently been developed into an extremely valuable laboratory tool, particularly from the standpoint of background discrimination, but the overall system complexity is prohibitive for space-based applications.

Rayleigh scattering is a considerably stronger process and is also attractive in the sense that a source of virtually any wavelength may be used. Since it is an elastic process, however, it is not species specific. In addition, unwanted scattering can be a crucial impediment. In many cases the reactants can be tailored in such a fashion as to yield a scattering cross section that remains essentially constant. Reports can be found in the open literature wherein two-dimensional spatially and temporally resolved measurements of this type have been performed. In certain situations, where the chemistry is well understood, the requirement for a constant scattering cross section may be relaxed.

Laser induced fluorescence has seen significant development over the last several years, specifically in the application to two-dimensional thermometry. The fluorescent emissions are, in general, relatively strong, but accurate quantitative interpretation is hindered by reaction dependent quenching rates. The emissions from naturally occurring species and from seeded flows have both been successfully employed. Single wavelength thermometry techniques rely on a constant or known mole fraction for the species of interest. Multiple wavelength techniques can overcome this restriction, but they result in greater overall system complexity, particularly with respect to the source requirements. The necessity for a wide selection of wavelengths to probe a number of different transitions represents the most significant hindrance for space flight applications.

Mie scattering from reactive seeding has also been used for reaction zone tagging. The most commonly used reaction is that of titanium tetrachloride with water. The extremely intricate chemistry of the reaction precludes quantitative interpretation. The production of corrosive by-products (HCl) is also a consideration.

Absorption techniques have received renewed attention with the advent of rapidly tuneable diode lasers. These lasers generally require cryogenic cooling for their operation and have limited life cycles. Substantial technical improvements are also required to control the selection of frequency bands. The major drawback of absorption methods is their line-of-sight nature. Where the symmetry or spatial extent of a process is not precisely known, tomographic procedures must be used. If the process of interest is transient, the hardware required for tomographic recording can become unduly elaborate. To detect weak absorptions on the order of one part in 10^5, or less, more sophisticated detection schemes such as frequency modulation are required.

Index of refraction methods, such as interferometry or deflectometry, also suffer from the same line-of-sight complications. The tomographic reduction procedures are computationally intensive, particularly if refractive corrections are included. In addition, a constitutive relationship must be known for the index of refraction as a function of the parameters of interest. If more than one parameter is to be determined, additional information, such as wavelength dependence, is required.

Velocity fields. - Methods for velocity measurements can be generally categorized into single-point and full-field techniques. The former accumulates the statistical distribution at a point and hence yields quantities such as the mean velocity, turbulence intensity, and shear stress. The latter yields velocities over a field of view, but contains very few samples at any given point. The interpretation is thus greatly complicated by the presence of turbulence. With the exception of tagging by multiphoton excitation processes, almost all velocimetry techniques require the introduction of seed particles to serve as scattering centers.

Laser Doppler velocimetry (LDV) is unquestionably the most accurate single-point method currently available. Extremely rugged and compact systems have been built using diode laser sources and fiber optic coupling sections. Sample volumes of a few hundred micrometers in extent and fractional percent accuracies for mean quantities are routinely achieved. The long time required to implement multipoint scans is the only significant drawback, but it is a significant one for combustion processes which are in many cases transient.

Full-field techniques are invariably predicated on a posteriori analysis. Film based recording techniques are usually selected because they have higher spatial resolution than other imaging devices. Sophisticated algorithms have been written which enable individual particle images to be computer tracked. These methods typically suffer from degraded performance in the presence of turbulent flows. Hybrid electro-optic techniques are a promising alternative, but they are largely in the early stages of development.

Near-Term Efforts

The near-term efforts consist of those diagnostic development activities which the workshop participants judged efficacious for beginning the project. Thus two-dimensional imaging was chosen as the most promising initial approach, based on its flexibility for several different kinds of measurements and a wide variety of experimental conditions. The initial emphasis would be on gas-phase measurements for simplicity and wider applicability. The full field imaging would give the largest amount of information simultaneously, even though it would be more qualitative than quantitative. An important characteristic is that it can readily be upgraded.

The development of the microgravity diagnostics during the near-term effort will advance from breadboarding to low gravity verification testing in the drop towers and airplanes flying parabolic trajectories. Reaction zone visualization, full-field temperature and velocity techniques, and imaging hardware were near-term issues that were discussed along with a comparison of low gravity facilities for verifying the breadboard developments and the required near-term improvements and modifications in laser systems for combustion diagnostics utilization in space.

Reaction zone visualization. - Visualization of the reaction zone could be accomplished by Mie scattering from reactively formed seed or by flame photoemission. There are several approaches to Mie scattering: seeding with particles, with titanium tetrachloride, and with oil droplets. Seeding problems would be similar to those described later under velocity measurements.

Rayleigh thermometry. - For Rayleigh scattering, tailoring the mixture to keep the Rayleigh cross-sections approximately constant from reactants to products is well documented. Calibration can be done in a constant density field. Fiber optic techniques are possible. In those cases where the cross-section can not be kept constant, interactive data reduction procedures can be implemented. The need to keep Rayleigh cross-sections constant was not seen as a major limitation for a wide variety of applications.

Thermometry via small filaments. - Small silicon carbide filaments (approximately 15 μm in diameter) have been used to visualize flame temperatures along a line. The flame can be profiled by translating the fiber. This gives a good qualitative picture of the temperature fields and can be made quantitative. With near infrared detectors (response near 1.6 to 1.8 μm) the temperature range that can be visualized is roughly 1000 to 2600 K. For lower temperatures a detector that is sensitive further into the infrared spectrum is required. This technique is able to show the location of flame fronts. This technique is simple and requires no lasers, but the filaments themselves are rather delicate and can't take a lot of abuse. The results can be photographed at, for example, 500 frames per second. Frequency response of the filament needs to be considered.

Velocity measurements. - Particle tracking experiments for velocity visualization can be done with two-dimensional imaging techniques. In order to achieve high framing rates and high resolution, photographic film is considered preferable to solid-state systems. Resolution of film can be equivalent to 2000 by 2000 pixels, or even 3000 by 3000 pixels, based on ASA 400 film, and without computer enhancement.

The difficulty with particle tracking is the necessity of seeding the system. In multiphase systems, such as liquid-vapor systems where surface tension gradients drive the fluid motion, particle seeding destroys the surface tension motion. Seeding is less a problem for gas phase experiments. In diffusion flame experiments, the convective flow of the gases themselves can be used to seed the system. In the absence of convective flow the problem is much more difficult as any seeding will disturb the flow (generally for very slow flow regimes). The particle size required to image the field and not settle out was suggested to be 5 to 10 μm. For a 2-μm particle the settling velocities at one g are a few millimeters per seconds, which is the same order of magnitude as the flow velocities being measured. At a one-to-one magnification these particles will be blurred and will appear 10 to 14 μm wide. The blurring is reduced by magnification, but the field of view becomes restricted. It was noted that in zero gravity, the particles will not settle out. The problem of rapid seeding, a fairly slow process at one g, was not satisfactorily answered in view of settling velocities.

Imaging hardware. - Considerations of the choice of imaging hardware include sensitivity required, spatial resolution, field of view, dynamic range and intensity of resolution, and framing and data transfer rates. For drop tower experiments particularly, but also for aircraft experiments, ruggedness is a requirement. For spectroscopic techniques, spectral discrimination is required.

Photographic film has capability for some imaging experiments, as was discussed in the section "Velocity measurements." Film will not be sensitive enough for fluorescence, Raman, or Rayleigh measurements, especially in the short duration available to these experiments. Pushing black and white film may achieve ASA 2000 or even possibly 4000, but this is still far short of an intensified solid-state array. Film would be the method of choice for Mie scattering where signal strength is high. In this case the ruggedness of photographic cameras and the high framing rates possible make this the best detection technique. For the 5-Second Drop Tower the film has to be able to take a vacuum. There are films that can be used, or alternatively, the camera can be placed inside a pressurized box.

For most of the desired measurements, an intensified array will be required. These are delicate items and the difficulty will be making them rugged enough for drop tower experiments. There is some experience meeting military specifications in night vision goggles, but they do not have to survive the same deceleration as in a drop tower.

Spatial resolution is limited for intensified systems because of the need to match a fiber bundle to the image element. Current intensified systems are limited to about 500 by 500. Kodak makes a 2000 by 2000 system, giving pictures of about 6-µm resolution. Most manufacturers will not intensify this because there is not a good match between the intensifier and the array. Intensified arrays have a relatively limited dynamic range of about 100 to 1 compared with about 10000 to 1 for unintensified solid state arrays. The Kodak system with its very small pixel size loses the dynamic range advantage.

Another trade-off is framing rate for intensity resolution. For most systems the maximum framing rate is 300 to 400 frames per second. The high framing rate systems give 6- bit resolution compared with 8 bits for video rates. The Spin Physics system allows very high framing rates but loses dynamic range and sensitivity. Intensification of this system was unsuccessful because the intensifier was unable to run this quickly. A 128 by 128 array reads out at about 400 Hz. The readout is limited to about 30 to 35 seconds before the buffer memory is filled. Slower framing rates (10 to 25 Hz) would be acceptable under certain conditions in microgravity experiments. Many of the interesting processes that differ from normal gravity are slow; otherwise buoyancy wouldn't affect them.

One limiting factor in the trade-off between resolution and speed is temporary storage. A system having both high speed and high resolution would require a greater band width of the entire system. The Spin Physics camera uses several individual A to D converters and splits up the array into different segments, each with its own A to D converter. That system allows 2000 full frames per second or up to 10 000 split frames. For pulsed laser-driven experiments the high framing rates are not generally useful at present because the only rapidly pulsed laser is the copper vapor laser, which does not have the coherence and beam profile properties of other lasers.

The Imacon systems that Marshall Long uses have a framing rate of 2×10^7 per second. The array is 4000 by 1000. The image is placed sequentially along smaller parts of the array and then later the whole array reads out. These systems are expensive and delicate and show worse performance than other intensified systems do.

There is project going on at Lewis in high-speed, high-resolution imaging as a long-term project so that the technology is available when the experiments become more developed.

Spectral selection is required with these imaging devices for spectroscopic experiments such as Raman, fluorescence, and emission. In general this is accomplished using narrow optical bandpass filters to isolate a spectral band. Certain experiments will require isolation of a complete molecular band. Others may require isolation of a particular line or small group of lines, which is more difficult using filters. Issues to consider are peak transmission and bandwidth of the filter, especially in the ultraviolet where peak transmission drops sharply. Available narrow band filters in the ultraviolet have only about a 10 percent peak transmission. Filters are also needed to block the laser light. Any given experiment will generally have a small number of species of interest. The number of filters required will therefore also be small. A rotating filter wheel allows selection of the spectral region. A possibility for generating tunable filters involves using solid state mixing of optical signals to down-convert into the infrared and get spectral selection by tuning the local oscillator. These experiments with Lehigh University are just getting started.

Comparison of drop tower and aircraft experiments. - Several experiments can be flown simultaneously on the KC-135. The recurring costs of KC-135 experiments are relatively low. The development costs are relatively high and accessing the aircraft can be a problem. Some aircraft experiments can be performed on the Learjet based at Lewis. The trade-offs in the choice of facility involve cost, access, and the duration and quality of the low gravity environment. The 2.2-second drop tower allows several experiments per day. Operational and material costs are low. The 5-second zero gravity facility allows one experiment per day. Several mechanics are required to operate the facility. The parabolic flight of the jet aircraft provides about 20 seconds of low gravity (at 10^{-2}g; the towers provide 10^{-5}g to 10^{-6}g). By free-floating the experiments in the aircraft, it may be possible to reduce the gravity level by an order of magnitude. Other trade-offs enter into the experimental design. For example, in drop tower experiments it was suggested that the laser light be brought in via fiber optics. Care needs to be taken to reduce scattered light from the walls of the experiment. For aircraft-based experiments the use of lasers is simplified. There is sufficient room and power available on board the aircraft to operate Nd:YAG lasers. Raman and fluorescence experiments are possible aboard the aircraft. The detectors are also simpler to operate in the aircraft. For towers the very small size of the drop packages and the high deceleration at the end of the experiment compel a lot of clever design considerations. Experiments involving delicate apparatus or requiring high electrical power are best conducted on the aircraft. The aircraft experiments have more stringent safety concerns, particularly where combustion experiments are involved. Time between experiment design and implementation varies with the facility. For the Learjet, which is controlled by Lewis, the experiment can be performed within a month or two provided all the safety requirements are met. For the KC-135, which has more competition for use, the lead time is six months. Experiments can be performed virtually immediately in the small drop tower once the package has been built. The larger drop tower has more competition for use, so facility scheduling is the limiting factor.

Required improvements in laser systems. - Improvements will simultaneously be required in fiber optics in terms of spectral bandwidth, capability to transmit high power pulsed laser light, transmission in the blue and ultraviolet ranges, and improvements in connectors, couplers, and terminators. Consideration should be given to nonlaser light sources for experiments where intensity and coherence are not issues. Development of more intense light sources with greater frequency coverage would be appropriate. Such sources might be useful in absorption experiments.

The main issues to consider in laser improvements are to make them smaller and hardier and to reduce their requirements for utilities such as power and cooling. High intensity and more rapid pulsing are also desirable.

Diode lasers are possible sources both for absorption and for LDV experiments. Improvements are needed in spectral stability, lifetime of the lasers, and power output. The elimination of the need for cooling tunable lead salt lasers is necessary. Diode laser LDV systems are in use now, and diodes could also be the source for Mie scattering experiments. Diodes would not be useful for Raman and Rayleigh scattering because they operate at the unfavorable infrared end of the spectrum rather than the blue where the scattering efficiency is much greater. Existing diode lasers are also much too low in power output for Raman experiments.

Diode-pumped Nd:YAG lasers show a lot of promise. The lasers have the potential for high power, high repetition rate, single mode operation, with low cooling requirements. Diode-pumped Nd:YAG lasers are being developed now and are hindered primarily by economic rather than technical concerns. An all solid-state laser would not have the problems of toxic gases or breakable glass tubes. It would be plausible to have a Q-switch module so the system could be either pulsed or CW, a module containing nonlinear crystals for harmonic generation and frequency mixing, and a dye module.

The limited tuning range of dye lasers means that each species is generally measured with a different dye. This means that dye changes have to be made, most likely by carrying multiple dye modules. Some spectral overlap occurs, which can be exploited, but these do not generally involve the most advantageous lines in terms of sensitivity to temperature variations. For example, there is some overlap among OH, CH, and NH in certain spectral regions, allowing all three species to be measured using a single dye. In the 248-nm region (KrF laser) hot oxygen, water vapor, and OH can all be pumped. Another problem with dye changes involves disposal of the waste dye. For short-term applications (aircraft) this is not a serious issue, but for long-term applications (notably space station) disposal of the degraded dye becomes a problem. Storage of the dyes and their flammable solvents is also a problem. Tunable solid-state lasers (e.g., alexandrite) may eventually eliminate the need for dye lasers. There may be some interest in solar-pumped lasers. The experimental window on an orbiting experiment would be 30 to 40 min.

Intermediate-Term Efforts

The intermediate-term efforts consist of those diagnostic procedures that are more difficult to undertake than were the techniques covered under the near-term efforts. Among the topics discussed were point measurements, the simultaneous measurements of multiple quantities, and the importance of nonoptical techniques.

Requirements for point measurements. - Point measurements will be required in addition to the full-field measurements described both for the greater quantitative accuracy possible with point measurements and to serve as calibration points for full-field measurements. The primary interest here is shuttle-based experiments. If possible it would be desirable to achieve point measurements even in some of the ground-based experiments. For example, if the two-dimensional images show counter-intuitive effects, measurements of temperature, species concentration, and velocity may be required early. In all the ground-based experiments, the problem is the short duration of the experiment and hence the difficulty of moving the measurement point around adequately. It would be nearly impossible to assemble a statistically significant number of point measurements under these conditions. It may be possible to choose the measurement points appropriately so that a small number of points would effectively supplement the full-field measurements. The choice of points would have to be done carefully so as not to skew the results. It is possible to scan the sampling point rapidly to cover a large volume in a small amount of time and use time correlations to determine the statistics at each point within the measurement volume. The scanning is done by moving the laser beam using, for example, rotating mirrors.

Velocity measurements. - For fuel nozzle spray work, velocity and droplet size measurements will need point measurements early on. Quantitative data are needed to support modeling efforts and to understand how the various parameters affect the phenomena. The main difficulty is that point measurements generally are time-averaged. The time-averaged problem can be alleviated somewhat by using the scanning technique described above. For velocity measurements, the number of readings is the number of particles passing through the scanning volume. A high scanning velocity allows high rates even in a low velocity field. For all velocity measurements seeding has the same problems described in the near-term discussion. Diode laser LDV is a promising technique. The system can be made compact. Hundreds of milliwatts output are available now, which is sufficient for LDV.

Species concentration. - A recognized way to measure species concentration is by laser-induced fluorescence. Raman may also be useful. LIF, CARS, and other Raman-based techniques all use the same type of lasers, that is, Nd:YAG-pumped dye lasers. When the technology reaches a point where these lasers can be flown on the shuttle, all these techniques become possible. Spontaneous Raman is probably too weak to be a realistic technique except in very high pressure experiments.

Simultaneous measurements of multiple quantities. - In addition to examining one parameter over the whole field, it is also worthwhile to examine more than one parameter at the same point and establish cross-correlations. This may be done with a single instrument or with a combination of instruments; for example, the CARS-LDV experiments that Larry Goss and others perform now. The interesting areas to probe using combined measurements were determined earlier in profiling measurements of a single quantity.

Calibrations. - Point measurements serve to calibrate field measurements. An example is thermometry using oxygen fluorescence. The fluorescence intensity is a monotonic function of temperature over the range found in combustion systems, and a measurement at one or more points allows the experimenter to determine the temperature throughout the field. Some similar techniques involve measurements that are not monotonic. More care is required in the interpretation of these measurements.

Nonoptical techniques. - An important point is that we not be constrained to consider optical methods exclusively. Often a nonoptical technique exists right now that will make the measurement, and make them more easily than an optical technique can, but these techniques are intrusive and may affect the data or may not provide the required quality of data. The participants were reminded that the purpose of the MCD project was to develop advanced diagnostic methods. Those methods already available and suitable for flight utilization are not subjects of this ATD project. However, nonoptical techniques, such as gas chromatography and mass spectrometry, which require development for space use, should be and are considered as proper subjects for this effort. Indeed, in some cases the point of pursuing laboratory-based optical measurements is to verify the nonperturbation of an intruding nonoptical device.

Mass spectrometry has the advantage of being able to detect multiple species. It will detect both stable species and radicals. For species heavier than a few atoms, where the optical spectra are very complex and often overlap, and mass spectrometry is probably a better diagnostic choice than laser techniques. If coupled with gas chromatography, it is possible to separate species before identifying them, thus simplifying the spectra. A mass spectrometer has been flown on the Viking probe to Mars.

Long-Term Efforts

The discussions under this heading centered on generic efforts such as the modularization and miniaturization of laser diagnostic systems for use aboard the space station and possible means for keeping the project current between the initial planning and the time when the technology developments generated from the project are actually used for the design of diagnostic instruments for the station.

Modularization/miniaturization. - Conceptually, laser systems can be compacted in volume and modularized such that the system can be plugged into an interface facility which supplies the diagnostics and the modular experiment with power, data acquisition, venting, cooling, liquid and gaseous fuel, etc. But the question of implementing the modularization of laser diagnostics system is directly affected by decisions, yet to be made, relating to the operation of the space station. Experimenters would like to have all the facilities and accommodations available aboard the station as they have in their one-g labs, including the presence of highly qualified research personnel, but economic and physical restrictions of conducting research in space inhibit the realization of this desire in the foreseeable future. Two feasible extremes for conducting experiments aboard the station exist. In one extreme the principal investigator (PI) would have available the volume of two 19-in. racks in which to contain the total experimental package, including the diagnostics, the data acquisition, storage, etc. The PI or an associate would conduct the test on the station and impose whatever changes in procedures or modifications in experimental requirements during the testing as necessary. This mode of operation is the most flexible and offers the PI the best control over the conduct of his experiment. The disadvantage with this procedure is the duplication of diagnostics development and experimental hardware development (i.e., similar systems will need to be redeveloped for each new experiment). Furthermore, the PI would be confined to the station for 45 days (the interval between shuttle visits) and the assigned rack space would not be available for other use during this time.

The other extreme in conducting combustion experiments aboard the space station consists of the maximum use of multiuser hardware, both the diagnostics and the experimental apparatus. Modular hardware would be designed for various classes of combustion experiments, such as gas jet diffusion flames, droplets and sprays, premixed gases, etc. (see classes of experiments in Microgravity Science Requirements Review section). The diagnostics would be designed either as integral with the experimental apparatus or as separate modules. The PI's would structure their experiments to accommodate this predesigned hardware. The latter being modular could allow for some adaptation specific for a particular set of experiments. The FES discussed earlier is an example of the multiuser facility concept. This modularized hardware with the PI's combustion experiment, along with the combustion modules of other PI's, is transported via the shuttle to the station and plugged into the combustion facility, the interface device discussed above, by the payload specialist. Upon completion of the testing, that module is removed from the combustion facility and is replaced by the test module of another PI.

Since the number and types of experiments (combustion, fluids, biological, etc.) are numerous and the size of the crew small (up to eight in the initial configuration), the crew members will have multiple duties in maintaining the station and conducting the experiment. The time and expertise they can give to any particular set of experiments would have to be limited. Thus, the experiments would have to be fairly automated, allowing for rather minor deviations in procedure. The activities of the payload specialist would be limited to monitoring, well defined tweaking, sample changes, venting, recharging, field maintenance, minor repairs, and other such duties. There may be some teleoperation capability, allowing the PI at a ground control center to direct the experiment. The disadvantage of this scenario is lack of flexibility in the configuration and conduct of the experiment by the PI, but it provides efficient utilization of the station and minimizes the development of diagnostic and testing hardware. Somewhere between these two extremes there exists a cost benefit optimum.

Assuming the acceptance of multiuser facilities and experimental apparatus on the space station, the modularization (and, of course, the miniaturization) of laser diagnostics would be desirable. In a sense, an optical bench is a modularized system with such modules as light sources, lenses, mirrors, filters, detectors, and hardware to support these components. Thus, the modularization of laser systems becomes one of scale or degree. It is possible to visualize a black box (module) containing the source, another box the optics, and yet a third being the detector. A supply of these modules could be stored aboard the station and, depending on the experiment, the proper set could be plugged into the combustion facility. Thus, full field measurements may be switched to point measurements by replacing the optical module. Such a system would probably require some tweaking and perhaps recalibration, but the convenience of this modularized system would be at the expense of flexibility. A more flexible system would be a small optical table where the payload specialist could rearrange the components of the system to match changes in the experiment much as is done in a one-g laboratory.

Since a laser system on an optical bench contains significant unoccupied space, the first step in miniaturizing without degrading performance would be to compress the components into a small volume. The laser source itself contains a lot of empty space, which can be compressed to substantially less volume. The challenge is essentially one of repackaging, but there exist the problems of maintaining focal lengths, beam diameters, etc. The development of solid-state laser sources offers yet another means of conserving space.

Assimilation of New Technology. - Laser diagnostics is a rapidly developing field producing new techniques or advancing current techniques every year. Thus, any project involving laser diagnostics, such as this MCD project, needs a mechanism for following these new or improved developments, to assess their applicability to the project and to assimilate the applicable techniques into the project. A mechanism of this sort is necessary for keeping the project current and must be a part of any MCD plan. Various mechanisms can be envisioned:

- Periodic workshops with laser development experts and microgravity combustion experimenters in attendance

- Session of an appropriate conference, such as the AIAA conferences, set aside for microgravity combustion laser diagnostics development presentations

- A NASA employed or contracted individual dedicated to tracking such development by personal interaction with developers and users, attending appropriate conferences and meetings, interacting with pertinent user groups such as the microgravity combustion discipline working group and the facility science user working group, etc., and evaluating the information gathered from these contacts for making recommendations to the project manager

- A standing committee of laser diagnosticians, laser developers, and microgravity combustion experimenters to meet periodically to assess the status of the project and make recommendations

- Selected laser diagnosticians to join the microgravity combustion discipline working group and periodically offer their recommendations

- Any combination of the above

Recommendations

The following recommendations were proffered explicitly or implicitly during the course of the workshop:

- Initiate the project with full-field visualization development efforts.

- Follow the visualization development with Rayleigh thermometry and follow that by laser-induced fluorescence (LIF) for thermometry and species mapping.

- Explore two-dimensional velocity mapping utilizing imaging methods or sequentially scanning laser Doppler velocimetry (LDV) methods.

- After full-field parametric developments, proceed to point measurements to gain greater accuracy and to provide calibration points for the full-field measurements.

- Pursue feasibility studies regarding simultaneous measurement of multiple parameters.

- Initiate studies to determine the optimum trade-offs in the degree of modularization and miniaturization of laser systems for the space station. Also to be included in these studies is the level of automation to be advocated.

- Provide on-going tracking of technological advances which may effect the design of microgravity laser diagnostic systems in order to keep the focus of the project current.

Current Microgravity Combustion Experiments

In place of the planned Summary of Discussions, four current microgravity combustion experiments were presented and the diagnosticians were invited to comment on the diagnostics employed in each of these experiments.

Ignition and Flame Spread Involving Liquid Fuel Pools
Howard D. Ross (Lewis)

The goal of this research is to increase fundamental understanding of the roles of gravity in the combustion of liquid fuel pools. In the liquid phase theory suggests that buoyancy should not be important, but some experimental work indicates it may be. If experimenters remove the effect of buoyancy in a low-gravity test, this question can be answered. In the gas phase the effect of buoyancy on ignition and flame spread is not well known.

Professor Sirignano at the University of California at Irvine is engaged in modeling the preignition state by studying the transient motion of the liquid and gas phases of an enclosed liquid fuel pool as the pool is heated from above. The code predicts flow patterns and temperature fields at different Grashof numbers. The experimental verification study of the code is being performed at Lewis. (A video of drop tower tests was shown.)

An experimental rig for studying the effect of gravity on ignition and flame spread involving liquid fuel pools has been built for testing in the drop towers.

The diagnostic issues in this program are techniques to measure the flow patterns and temperature fields in the liquid and gas phases of the preignition studies and to ignite and measure the flame spread rates in the flame spread studies.

Solid Surface Combustion
Sandra L. Olson (Lewis)

The purpose of this effort is to study the effects of low-velocity forced flow on flame spread over a thermally thin fuel. To establish a baseline of material flammability in low gravity, drop tower tests were performed on thin cellulose paper in a quiescent environment. Results indicated that flame extinction in low gravity is dominated by heat losses, whereas in normal gravity, extinction is dominated by convective effects. Flame spread rates at elevated oxygen concentrations are similar in normal and low gravity, but at lower oxygen concentrations, low gravity flames spread more slowly.

The flowing environment low-gravity testing will be performed on thermally thin solid fuels in an experimental apparatus referred to as a combustion tunnel, and this apparatus will be dropped in the Lewis drop towers. The tunnel diameter will be 20 cm, the flow range will be 5 to 100 cm/sec at 2 to 3 atm.

The diagnostics issues involved in this study include the visualization of dim blue flames, full-field velocity and flame zone measurements, temperature measurements of the gas and solid phases, and nonperturbing species measurements.

Fuel Droplet Vaporization
Patrick Farrell (University of Wisconsin)

Droplet vaporization is of interest because it takes place in the spray combustion of rocket and diesel engines. Droplet vaporization and breakup is being studied under conditions of very high pressures and temperatures. For many practical fuels, these ambient conditions are above the critical point of the fuel. Such conditions will strongly affect the rate of vaporization and the surface tension and thus the breakup of the fuel droplet. A microgravity environment will permit experimenting with a floating motionless droplet that can be nonintrusively studied. A one-dimensional transient diffusion model has been developed that will be compared with the experimental results and aid in the fundamental understanding of supercritical droplet vaporization. Experimental measurements will include vaporization rate, droplet distortion and break-up, and temperature and concentration profiles around the droplet.

The diagnostic issues in this project are the measurement of droplet diameter versus time, gas phase temperature and species concentration, and liquid phase temperature.

Gas Jet Diffusion Flame
Dennis P. Stocker (Lewis)

The objective of this study is to gain a better fundamental understanding of the effect of buoyancy on laminar gas jet diffusion flames that will aid in defining the hazards and control strategies for fires in the low gravity environment of space as well as to improve the understanding of earthbound fires. The approach is to obtain measurements from low-gravity experiments (drop tower and KC 135 aircraft) that include flame-shape development, flame extinction, flame color and luminosity, temperature distributions, species concentrations, radiation, pressure, and acceleration. These measurements will be used to validate a transient numerical model that reflects current understanding of the important phenomena that control gas jet diffusion flames.

The diagnostics issues in this study are visualization (flame shape, height and extinction conditions), radiometry, full-field temperature and velocity profiles, and species identity.

Departure

These presentation and the discussions ended the formal proceedings of the MCD Workshop. The workshop participants who wished to do so were given a tour of the 5-Second Zero Gravity Drop Tower Facility. All the participants were thanked for their contributions and for making the two-day affair enjoyable, interesting, and productive.

APPENDIX A
MICROGRAVITY COMBUSTION DIAGNOSTICS WORKSHOP PARTICIPANTS

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15. Supplementary Notes

16. Abstract

Through the Microgravity Science and Applications Division (MSAD) of the Office of Space Science and Applications (OSSA) at NASA Headquarters, a program entitled "Advanced Technology Development" (ATD) was promulgated with the objective of providing advanced technologies that will enable the development of future microgravity science and applications experimental flight hardware. Among the ATD projects one, Microgravity Combustion Diagnostics (MCD), has the objective of developing advanced diagnostic techniques and technologies to provide nonperturbing measurements of combustion characteristics and parameters that will enhance the scientific integrity and quality of microgravity combustion experiments. As part of the approach to this project, a workshop was held on July 28 and 29, 1987, at the NASA Lewis Research Center. A small group of laser combustion diagnosticians met with a group of microgravity combustion experimenters to discuss the science requirements, the state-of-the-art of laser diagnostic technology, and plan the direction for near-, intermediate- and long-term programs. This publication is the proceedings of the workshop.

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